MONTREAL PROTOCOL
ON SUBSTANCES THAT DEPLETE
THE OZONE LAYER

UNEP

1994 Report of the
Refrigeration, Air Conditioning and Heat Pumps
Technical Options Committee

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The text of this report is composed in CG Times.
Composition and co-ordination: Lambert Kuijpers (Chair TOC)
Layout: Frank Engels
Reprinting: UNEP Nairobi, Ozone Secretariat
Funding of reproduction: Ministry of Housing,
Spatial Planning
and the Environment,
the Netherlands
Date: 30 November 1994

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Printed in Kenya; 1994.

ISBN 92-807-1455-4

1994 Report of the Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee

for the
1995 Assessment
of the

UNEP

MONTREAL PROTOCOL ON SUBSTANCES THAT DEPLETE THE OZONE LAYER

pursuant to
Article 6
of the Montreal Protocol;
Decision IV/13 (1993)
by the Parties to the Montreal Protocol

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Acknowledgement

The UNEP Refrigeration, AC and Heat Pumps Technical Options Committee acknowledges with thanks, the outstanding contributions from all of the individuals and organisations who provided technical support to committee members. In developing this report, particularly the section chairs and cochairs were instrumental.
The names, addresses and contact numbers of all section chairs and members of the UNEP TOC Refrigeration, AC and Heat Pumps can be found in Annex II.
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Reproduction of draft copies and of the final copies of the Refrigeration, AC and Heat Pumps Technical Options report has been made possible through funding by the Netherlands Ministry of Housing, Spatial Planning and the Environment.

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Executive summary: refrigeration, air conditioning and heat pumps

Refrigerant data

This section considers the properties of refrigerants for use in the vapour compression cycle. Namely, the vast majority of present equipment utilises the vapour compression cycle because of its simplicity and good efficiency. The dominance of this cycle is not likely to change simply due to the need to replace the chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs); it will prevail even after the phaseout of the latter substances.

The ideal refrigerant will satisfy a set of criteria, including chemical stability, nonflammability, and low toxicity, the need for favourable thermophysical properties, and other, more practical, considerations such as materials compatibility. Although many types of fluids have been used as refrigerants in the past, the halocarbons dominate today because their unique combination of properties proved to best satisfy these sometimes conflicting requirements. Experience with the CFCs has shown, however, that substances possessing the chemical stability desirable in a refrigeration system can, when emitted, accumulate in the atmosphere and cause unacceptable environmental harm.

Because of the success of the CFC refrigerants, most of the efforts to develop replacement refrigerants have focused on a set of hydrogen-containing, but otherwise similar, compounds. At present, hydrocarbons and other simple inorganic compounds (the so-called "natural refrigerants") are receiving increased interest. This choice is confirmed by theoretical studies which indicate that simple molecules of relatively low molecular mass and with normal boiling points similar to present working fluids would be excellent refrigerants. These fluids include HFCs -134a, -152a, -125, -32, -143a and -23, and HCFCs -22, -123, -124, and -142b. These fluids are the popular choices for the immediate replacement of the CFCs; some of these fluids are also acceptable long-term replacements. Mixtures of these fluids are also good candidates.

The light hydrocarbons such as propane, butane, and isobutane will likely see increased use; since they have excellent environmental and thermophysical properties. However, they are flammable, and must only be used in systems which operate safely with flammables. Ammonia, a refrigerant that currently dominates certain applications, is being considered for a broader range of uses; it is, however, flammable and toxic. Water, carbon dioxide, and air may also be used as refrigerants, but require different types of equipment. Additional classes of fluids, such as the fluorinated propanes and fluorinated ethers, show some promise as refrigerants; such fluids, however, are in the very early stages of development and would not be available in large quantities for many years.

Data of a variety of types are required to evaluate a potential alternative refrigerant. The thermophysical (i.e., thermodynamic and transport) properties of a fluid determine its energy efficiency and heating or cooling capacity in equipment and are essential for equipment design. Properties related to health and safety (toxicity and flammability) can determine whether a fluid is suitable for a particular application. Data on materials compatibility are required to design reliable equipment. The environmental characteristics of ozone depletion potential (ODP), atmospheric life, and the greenhouse warming potential (GWP) taken together with the coefficient of performance of the refrigeration system and emissions due to leakage, servicing, and disposal (that is, the total equivalent warming impact, or TEWI, concept) will determine whether a fluid should be considered an acceptable alternative to the CFCs.

Only simple parameters such as normal boiling point and molecular structure are needed to conduct a coarse screening among many candidates, while widespread commercial use requires extensive, accurate data of all types. In section 2, the needed data are described and categorised, and the available data are summarised for the leading candidate refrigerants.

The greatest impediment, however, to selecting, developing, and commercialising alternative refrigerants is the uncertainty regarding the relative weight to be given to ozone depletion potential, global warming potential, energy efficiency, and safety factors such as flammability.

Domestic refrigeration

Approximately 64 million refrigerator-freezers are manufactured world-wide each year. Hundreds of millions are currently in use. The majority of these units employ the vapour compression cycle with CFC-12 as the working fluid, typically containing between 20 and 600 grams of CFC-12 refrigerant, globally. The efficient use of energy by refrigerator-freezers has assumed more importance due to the emphasis on reducing global warming.

Advanced vapour compression cycles employing separate evaporators in the fresh food and freezer compartments are receiving significant research attention. A circuit employing zeotropic mixtures and configured in the manner prescribed by Lorenz and Meutzner has been predicted to yield efficiency gains up to 26%; gains of 15% have been experimentally realised to date. Several patents have been issued on alternative two-evaporator configurations for use with constant boiling refrigerants. Efficiency gains of the order of 20% to 30% are predicted. Continuous compressor capacity modulation is another modification estimated to provide efficiency improvement of the order of 10% to 20%.

As new equipment alternatives to CFC-12, candidates have been assessed versus criteria encompassing environmental acceptability, safety, reliability, efficiency, process capability, availability and cost. Regional differences in refrigerant choice are driven by variations in consumer lifestyles and preference, government regulations, and industry offerings. Two refrigerants dominate current implementation efforts throughout the world. HFC-134a is the preferred alternative in the Americas, Asia/Oceania and selective applications in every region of the world. It is nonflammable and has zero ozone depletion potential. HC-600a is the alternate being widely adopted in Europe. It is flammable, has zero ozone depletion potential and a greenhouse warming potential approaching zero. Other alternative refrigerants receiving regional or niche product consideration are: HFC-152a, HC-290/HC-600a blends and the R-401A/B and R-409A blends (HCFC/HFC ternary blend).

Product configuration is a critical parameter for assessing risks. The safety aspects of each unique product configuration must be rigorously assessed. Substantive product redesign, possibly including new concept introductions, will be required to alleviate safety concerns with the use of flammable refrigerants for no-frost refrigerator-freezers.

Proof of concept demonstration with resonating piston, Stirling coolers indicate efficiencies comparable to current refrigerator-freezers. High entry investment, no long term reliability information and no demonstrated efficiency advantages over conventional systems constrain interest. Thermoacoustic refrigeration, sonic compression and linear compressor technology are promising new technologies. Broadened general insight is necessary for informed decisions regarding applicability. Absorption cycle refrigeration is not expected to penetrate beyond its historic niche segment.

Manufacturers will continue to service existing refrigerator-freezers with CFC-12 as long as it is available and less expensive than other retrofit candidates. Since retrofit options are limited, the HCFC/HFC ternary blends could achieve significant usage. HC-290/HC-600a hydrocarbon blends would function well, but must be carefully assessed for application for each unique configuration from a safety perspective. Appliances that have not been designed for their use should not apply flammables in servicing if not the appropriate safety measures have been taken. HFC-134a is not a practical alternate for retrofitting. Part of the CFC-12 service demand will be satisfied by recovered CFC-12 during field service or by recovery at disposal and reclamation to acceptable purity standards.

CFC-12 usage for domestic refrigerator/freezers was 9,100 metric tonnes in 1990, 75% of this amount consumed in the developed countries. It is estimated that 70% of the production units will be converted to HFC-134a, and 30% will be converted to isobutane. Further use of isobutane will be mainly determined by the fact whether -compared to other non ozone depleting options- high energy efficiencies can be achieved. HCFC usage is not expected to exceed 3% of total refrigerant demand. Regarding transition timings, it is currently estimated that 85% of the developing (Article 5(1)) countries new unit production and 15% of developed countries new unit production will be using CFC-12 in 1995. By 1997, 70% of Article 5(1) countries' new production will still be using CFC-12 while other countries will be CFC free. Article 5(1) countries new production usage is expected to be down to 10% by 2000 and CFC free by 2005.

Categorising Article 5(1) countries by their apparent strategic intents toward domestic refrigerator-freezers -i.e., in finished product import only, finished product manufacture for domestic use and/or export, and/or hermetic component manufacture for domestic use and/or export- provides insight toward their technology and timings needs as well as probable technology access options. Significant product or component import/export activities with developed countries will require accelerated CFC phaseout timing, consistent with the needs of the trading partner(s). Service, retrofit and reclamation technologies are viewed to be particularly acute needs for Article 5(1) countries.

Considering processing technology considerations, the compatibility of materials, chemicals and components processes must be understood to maintain quality and reliability standards. Heightened discipline for manufacturing cleanliness and process control are essential for the successful application of HFC-134a. Required purity levels for hydrocarbon refrigerants are still being debated.

Commercial refrigeration

Commercial refrigeration encompasses equipment and systems ranging from a fraction of one kW to many hundreds of kWs extending across the food industry applications to hospitals, hotels, corner shops through to engineering quality control applications.

CFC consumption, primarily CFC-12 and R-502, has been reduced in the last 3 years in most industrialised nations primarily by switching over to HCFC-22 and HCFC-22 containing blends and to a much lesser extent to HFC blends. There is still a reluctance to make changes until it is seen that there is a freedom from service related problems and that reliable and sound engineering procedures exist, thereby minimising risks and costs.

Areas of uncertainty do exist especially with the small unitary equipment utilising hermetic compressors. This is particularly the case where high temperature or tropical operating conditions exist and where the scope for retrofitting is limited.

The phaseout of CFCs by 1996 appears feasible and more experience with the use of HFCs is needed to prepare for the eventual phaseout of HCFCs within the allotted time scale.
For new equipment the move out of CFCs has generally been more pronounced, especially to HCFCs, however the subsequent use of HFCs for many operators is dependent on equipment manufacturers development and testing to produce a price competitive product and reliable procedures.
Advice for those facing the decision to move from CFCs to HCFCs and/or directly to HFCs, is available from various sources and free exchange of such information should be encouraged to accelerate the conversion progress.
Technology transfer to developing countries, particularly in respect to the sharing of practical experience identified in this section could be expanded by communicating successful retrofit and new applications case histories, to facilitate the phaseout of CFCs.
Of equal importance is the international acceptance of HFCs as the logical successor of CFC and HCFC for the majority of commercial applications, notwithstanding the progress in many areas to investigate the use of non-fluorocarbon and not in kind alternatives.
Reduction of leakage, recovery of refrigerants coupled with a general reduction from service/breakdown related activities continue to improve in commercial refrigeration. This is of considerable significance when applying the TEWI concept to the selection of refrigerants due to the contribution of high leakage rates on the direct effect of global warming. With reduced emissions currently evaluated HFCs are most viable when used at higher system efficiency levels, making the TEWI favourable.
Future trends include designs with reduced refrigerant charge, an increase in self-contained (unitary) display cases, more efficient compressors, improved electronics for diagnostics and efficiency improvements plus encouraging moves to secondary refrigerants for some applications.
The use of primary refrigerants such as ammonia and HFCs require experienced, skilled engineers. To provide the training to produce engineers with such skills presents a major challenge which must be addressed, if progress is to be maintained.

Cold storage and food processing

Cold storage and food processing is one of society's most important applications of modern refrigeration techniques. Cold storage and food processing include a wide variety of applications especially if cold storage is not restricted to the simple storage of foods and indeed when food processing is extended to cover such fields as the freezing, dairy and brewing industries.

Foods such as dairy products, fish, meat, fruit and vegetables are stored and distributed in huge quantities in a chilled condition. Frozen foods are generally stored in the temperature range -18 to -30 °C. Some fish products intended to be eaten raw are stored at temperatures even lower than -50 °C. Food processing, which includes freezing, may take place at air and refrigeration temperatures down to -40 °C and lower.
The industrial cold storage and food processing sector is a vital element in the safety and health of the world population. The preservation of the world food supply is vital to stability and economic growth throughout the world. The world frozen food production in 1992 was approximately 27.5 million metric tonnes but represents only a small part of the total food volume preserved by refrigeration. As the transportation and distribution infrastructure of the developing countries improves, significant increases in the need for cold storage is likely to occur. This will probably follow the same patterns as in the

developed countries and will eventually stabilise where the chilled food is about 10 to 12 times that of the frozen products.

Since the 1991 assessment the world has seen a return to the use of ammonia in the large scale chilling, freezing and cold storage systems. Simultaneously, strenuous efforts have been made to reduce the size of the ammonia charge in large systems by using plate-type heat exchangers and secondary refrigerants or by using low charge, low pressure receiver ammonia systems which avoids using circulation pumps that require a large refrigerant volume.

In countries where there are severe restrictions on using ammonia, other refrigerants are being examined as replacements. One of the past alternatives to ammonia has been HCFC-22. However, because it is slated for phaseout, HCFC-22 will eventually become unavailable requiring the current systems to either be replaced or retrofitted with other alternatives. One of the current replacements for CFC-12 is HFC-134a. However, HFC-134a has only limited use as a replacement in this application because CFC-12 is not widely used in cold storage and food processing. Another widely used refrigerant in this application is R-502 which has a series of alternatives on the market in the form of blends. However, the "blends" that replicate the properties of R-502 are slightly more expensive, many contain HCFC-22, and many have been criticised for their global warming potential, which is still well below R-502.

While other refrigerants such as hydrocarbons, carbon dioxide and water may have a role in cold storage and food processing they are currently not expected to become a significant portion of the refrigerants being used in these applications.

Currently, there are no alternative technologies available that will play an important role in the replacement of the existing equipment used in this sector.

Retrofits in this sector while possible are difficult to actually implement. Generally speaking ammonia can not be used as a direct substitute in equipment not specifically designed for its use. The current halocarbons being extensively used (HCFC-22 and R-502) do have suitable direct "drop-in" alternatives, however, may require redesigned systems for truly effective, efficient operation. These factors tend to mitigate against retrofits and move the users toward other approaches (such as extending the life of the system by recovery and recycle of refrigerant, stockpiling, and refrigerant conservation\leak prevention activities). Currently, replacement systems must be specially designed and produced for the specific situation.

Currently, ammonia is the most readily available, environmentally acceptable refrigerant for food processing, chilling, freezing and cold storage. However, a major problem is finding ways of using ammonia acceptably in countries that have severe restrictions on its use based on safety concerns and legal liability precedents. A reasonable approach to general acceptance of ammonia would seem to be system re-designs to reduce refrigerant charge, produce automatic oil return and allow operation of unoccupied engine-rooms. Significant progress has already been achieved in this area but general acceptance of ammonia in the USA and Japan may continue to be slow. The old-fashioned style of large charge, pump circulated ammonia systems will always play a role in industrial size for large Food Processors and Cold Storage. However, non-pump circulation overfeed systems will play an increasing role. Indirect systems with low charge ammonia circuits (50 - 100 kg) placed outside buildings and on the roofs of buildings will also become more common. These small charges can be easily handled in the event of a leak and ammonia, one of the very few refrigerants lighter than air, will disperse upwards when released.

Industrial refrigeration

Industrial refrigeration covers a wide range of uses and operating conditions, primarily within the chemical, petrochemical and pharmaceutical industries, the oil and gas industry, the metallurgical industry, industrial ice making and sports and leisure facilities. Most systems are situated in industrial areas without public access. Therefore, toxic and flammable refrigerants, like ammonia and hydrocarbons, can often be safely used.

In developed countries CFCs are already virtually phased out in new industrial systems, only some 2500-3000 tonnes/year is required for service purposes. This demand will decline gradually, and is expected to die completely out in 10-15 years. Many Article 5(1) countries have decided to accelerate CFC phaseout, and CFC consumption is expected not to increase above current level of 500-1000 tonnes/year. After the year 2000, CFC use is likely to fall off also in these countries.

Annual HCFC consumption for industrial purposes in the developed countries is believed to be in the order of 13000 tonnes/year, or five times current use of CFCs, while Article 5(1) countries are expected to consume equally much HCFCs and CFCs. HFC consumption world-wide is currently believed to be less than 1000 tonnes per year.

The trend with respect to selection of replacement fluids for the CFCs varies markedly. In response to the outlook for more stringent HCFC regulations in Europe, many European countries have turned to ammonia, which has gained up to 70-80% market share for new installations.

In the United States and Japan, HCFC-22 has been the most common CFC alternative so far, and will most probably continue to be the first choice. Ammonia is expected to gain shares also in these markets, but less than the hydrofluorocarbons (HFCs), which are expected to remain significant in the long term. While technology with HFC-134a is considered to be mature for new industrial applications, HFC blends may still require a certain period to reach full maturity.

Technically, ammonia can be used for most industrial applications (ref. current development in some European countries), and it should always be considered a candidate; however it may imply that national regulations may need to be updated to permit its use. New technological developments have enabled strong reductions in system charge, and furthermore, made ammonia technology cost competitive in more applications.

Existing CFC systems, containing some 30,000 tonnes of chemicals, represent the greatest challenge in the short term. In principle, most installations can be retrofitted to use a non-regulated fluid. On the other hand, systems using BFC-13 (which is, in fact, halon-1301) make an important exception, since no fluid with similar properties exists.

Technology to retrofit CFC-12 industrial systems to use HFC-134a is fully mature in 1994, while change-over from R-502 to an HFC blend ,e.g. HFC-404A, will be available by the mid 1990s. Proven HFC blend technology may be available towards the end of the decade. Retrofit to use ammonia may be feasible in some cases.

Restricted availability of qualified service engineers to do the retrofit work may become a serious limiting factor in the short term.

Reduced emissions and recovery and reuse will play an important role in the short term to keep existing systems in operation. Nonetheless, shortage of refrigerant may force premature decommissioning. Possible reductions in energy consumption and improved flexibility with modern technology may reduce the cost effects for the end users.

A "most likely" scenario regarding the state of current stock of systems by the year 2000 implies an even distribution among retirement (natural and premature), retrofit and operation on recycled/stockpiled fluid.

HCFCs will be required to meet refrigerant demand in an interim period, since neither technology nor supply of chlorine free alternatives will be available in the near term. It is believed that up to 10 years may be required to enable industrial refrigeration to cope completely without HCFCs.

In the industrialised countries, HCFC consumption is likely to fall slightly off during the rest of the nineties, while a strong acceleration in the reduction is foreseen thereafter. By 2005, HCFC demand is believed to be only half of current consumption. A certain portion will be covered by reuse.

During the next decade, HCFC consumption in Article 5(1) countries is expected to nearly double, but will still be comparatively low by 2005 (1500-2000 tonnes/year). To minimise costs and ensure that best technology is identified for all applications, HCFCs should be available 5-10 years longer in Article 5(1) countries compared to developed countries.

HFCs will gain increased importance both for retrofit and new installations towards the year 2000. Consumption figures world wide will most probably exceed those of HCFCs by 2005 or shortly thereafter.

Change-over to ammonia will normally imply improved energy efficiency, while reference cycle efficiency will be lower with some of the new fluids. This may be compensated for by system optimisation and computer based regulation and control. On average, and in a first instance, energy consumption is expected to remain practically unchanged.

Air conditioning & heat pumps (air cooled systems)

The product categories included within the unitary (air cooled) product group are ducted and non-ducted split systems, single package room air conditioners and commercial single and multi-zone packaged air conditioners (the term air conditioners is assumed to include heat pumps). Nearly all of these products utilise HCFC-22 as the refrigerant. Globally, unitary (air cooled) air conditioners account for approximately 32% of the total world consumption of HCFC-22.

The estimated quantity of refrigerant contained in the installed population (approximately 214 million units) of these products is estimated to be 364,000 metric-tonnes. The 1994 HCFC-22 demand to manufacture and service this category of products is estimated to be 85,000 metric-tonnes.

Several promising HCFC-22 alternatives are currently under investigation. These alternatives include hydrofluorocarbons (HFCs), hydrocarbons (HCs) and a few naturally occurring compounds (ammonia). The majority of the HCFC-22 replacement candidates has zero ozone depletion potential. At this time the most promising HCFC-22 replacement candidates for this class of products are the HFC compounds. The HFC compounds have been extensively evaluated through the ARI AREP program and through many other research programs within the international community (section 14). The results of this research indicate that several HFC compounds could be suitable replacements for HCFC-22.

The HFC compounds have been criticised because of their direct global warming potentials. However, it is important to consider both the direct (portion caused by the refrigerant) and indirect (portion resulting from the energy required to operate the appliance during its lifetime) of the global warming impact when comparing different refrigerant options. For unitary equipment, the indirect effect can represent over 90 percent of the total global warming impact. The Total Equivalent Warming Impact (TEWI) is a factor which combines these two terms for a refrigerant. The TEWI values for the HFC refrigerants are equal or lower than for most of the other alternative refrigerants.

Equipment using alternative refrigerants is expected to be available in the 1996-1998 time period. Widespread availability is not expected to occur until 2000-2005.

An analysis of the demand for HCFC-22 was made assuming three different conversion rates: pessimistic, optimistic and most likely. The peak demand for HCFC-22 for this category of products was calculated to be approximately 95,000 metric tonnes with the peak occurring between 1998 and 2005. The demand for new HCFC-22 for these products should decline to between 10,000-30,000 metric-tonnes by the year 2015 versus the 1994 demand of 85,000 metric-tonnes. This analysis used to generate this estimate assumed a fairly aggressive recovery/recycling effort on the part of the world community. Should the world community fail to adopt aggressive refrigerant recycling programs shortages of HCFC-22 could occur during the next decade.

The primary technical concerns of the developing countries are: adequate supplies of HCFCs to service existing equipment and equipment manufactured before the HCFC phaseout date dictated by the Protocol, adequate supplies of alternative substances and technologies and concerns over the cost and safety of the alternative refrigerants and technologies.

Data on the cost of these refrigerants and the redesigned systems in which they would be applied are just now being evaluated by researchers. Some of these technologies are ideally suited to developing countries. Technologies which are complex and in their early stages of development will probably be too costly or complex for consideration by developing countries.

Equipment and operating costs are real barriers to the entry of larger residential and commercial unitary products into a country. If the benefits of air conditioning are to be experienced on a wide scale, incremental costs must be kept to a minimum. It is therefore important to develop alternative refrigerants and technologies which are both environmentally safe and cost effective. Technologies which are environmentally safe but also expensive and complex to implement would be a detriment to rapid conversion in developing countries.

Air conditioning (water chillers)

HCFC-22 has been used in small chillers employing positive displacement compressors and in very large chillers employing centrifugal compressors. CFC-11 and CFC-12 have been used in large centrifugal chillers. Due to the CFC phaseout, CFC-11 and -12 have been essentially replaced in new equipment production by HCFC-123 and HFC-134a, respectively. To date, no alternate has displaced HCFC-22 in the small and very large chillers.

HFC-134a is sometimes used in positive displacement water chillers. HCFC-123 is an energy efficient refrigerant that meets the basic design requirements for low pressure centrifugal compressors. This accounts for its use in centrifugal chillers in the 350 to 5000 kW range. HCFC-22 is used in the largest centrifugal chillers, from 1000 kW up to 35000 kW.

CFC-114 has been used in some centrifugal chillers, particularly those in naval vessels. These applications are expected to be converted to HCFC-124 or HFC-236fa, or replaced by HFC-134a chillers.

New equipment and refrigerants

The planned HCFC-22 phaseout has led to intense activity to find and characterise appropriate alternates. The refrigerants which appear to be most promising in terms of their ability to satisfy the performance and safety criteria are the blends of the HFCs. Azeotropic mixtures are under consideration as HCFC-22 replacements because they tend to act as single component refrigerant [i.e., the vapour and liquid composition at a given temperature and pressure is constant]. However, based on a very extensive search of alternatives, it is clear that there is no drop-in replacement for HCFC-22 in chillers with flooded evaporators today, nor is one foreseen. One implication of this is that any further acceleration of the phaseout of HCFC-22 would have serious consequences for the stock of HCFC-22 chillers in service at the time of the phaseout.

HFC-134a is being used in positive displacement water chillers as a zero-ODP substitute for CFC-12. A number of other zero-, or near-zero-, ODP refrigerants with volumetric flow rates in the range suitable for positive displacement chillers have been suggested. Examples are HFC-32, HFC-125, HFC-152a, HC-290 (propane) and R-717 (ammonia). These refrigerants are not attractive to designers of water chillers for commercial buildings.

Centrifugal compressors are the most efficient technology in their range of applications, 500 to perhaps 35000 kW (200 to several thousand tonnes capacity). The CFCs have been replaced by HCFC-123 and HFC-134a, respectively, but HCFC-22 is expected to be used in new equipment for at least another decade. Other refrigerants suggested for centrifugal chillers are HFC-143a (and maybe HFC-152a), and the fluoroethers E-134, E-143, and E-245ca. These compounds are either flammable or have no toxicity assessments at this time and in some cases have very limited thermodynamic data available. HFC-245ca is a potential long-term alternative to HCFC-123. More work is necessary to determine the efficiency of HFC-245ca as a refrigerant and to define any fire risks associated with its use in chillers. Nonflammable azeotropes containing HCFC-123 are another alternative for reducing the amounts of HCFC-123 used in chillers. Two isomers [ea and fa] of HFC-236 are being considered as replacements for CFC-114 which is used in special applications such as naval vessels.

Absorption is a tried and proven technology that is mass produced and well supported with a cadre of experienced technicians. This past decade, two-stage absorption chillers have been developed and produced with primary-energy-based efficiencies that approach 50% to 60% of those of vapour compression systems. Three-stage absorption systems are being developed to achieve efficiencies even closer to vapour compression systems. However, absorption chillers are inherently larger and considerably more expensive than vapour-compression chillers so absorption systems have had only limited market success in the western world. However one should emphasise that they are used to take advantage of waste heat so that they can be very economical in spite of the higher cost.

Retrofits

No substitute refrigerant can be used as a "drop-in" for CFCs with the exception of HFC-134a in some R-500 systems. HCFC-123 became available in 1989 to retrofit existing CFC-11 chillers. It is a more aggressive solvent than CFC-11. Non-metallic materials may have to be replaced with materials which are compatible with HCFC-123. HFC-134a became available in 1989 for retrofit in centrifugal chillers. Its use requires about 15% higher tip speeds than CFC-12, so impeller and/or gearbox replacement may be necessary. HCFC-124 has been suggested as an alternative to CFC-114 in centrifugal chillers such as those used in naval applications, as has HFC-236fa. There are currently no satisfactory replacement refrigerants for use in existing equipment designed for HCFC-123 or HFC-134a, nor are any needed in the near future. For equipment now using HCFC-22, zeotropic and azeotropic mixtures of HFCs are being developed.

The HCFCs are required as transition and long term refrigerants respectively until at least the 2020-2030 period. HCFCs are needed to allow the most rapid phaseout of CFCs in those critical applications such as air conditioning and refrigeration where the HCFCs are the best alternatives available. Improved design and maintenance of systems to reduce leakage, design to minimise refrigerant charge quantities in systems, improved service practices, and reclaiming of refrigerant during servicing are practical and reasonable ways to reduce the emissions of HCFCs into the atmosphere, thus minimising adverse environmental effects.

HFC-134a will play an important role in the transition away from CFCs, particularly as a replacement for CFC-12. However, HFC-134a is not able to overcome the need for HCFC-123 and HCFC-22. There are no other good near-term alternatives to the continued use of HCFCs.

Transport refrigeration

Transport refrigeration includes refrigeration in ships, railcars, containers, swap bodies and road transport equipment, and also relates to transport air conditioning. New equipment and retrofit options have been identified, as have servicing needs and the impact of HCFC phaseout.

There are approximately 33,600 ships in excess of 300 tonnes gross, all of which use some forms of refrigeration. Fully refrigerated cargo ships and refrigerated container ships number about 1,500. HCFC-22 is virtually universal as the refrigerant for new cargo refrigeration equipment, but 1993 marked the return of ammonia in a few new ships. This has yet to be demonstrated as a commercially viable option for widespread use.

At the end of 1993 there were 252,000 integral refrigerated containers in use, of which about half were less than 5 years old. Since 1991 there has been an almost universal acceptance of HFC-134a for new units, and there have been moves to HCFC-22 and various blends such that there is no need for CFCs for new container equipment. Retrofit options for existing plant have been developed but have yet to be adopted on a large scale.

Manufacturing rates for road transport refrigeration equipment are around 100,000 per year, and new equipment from major producers is moving rapidly away from CFCs, including R-500 and R-502.

The currently available options for both retrofits and new equipment are bewilderingly large, and there is a need for much more application-specific testing to determine optimum solutions. This situation appears likely to become even more complex whilst manufacturers compete for the future refrigerants market.

There are no proven direct alternatives to HCFC-22, and HCFCs are likely to be required as components in economically viable retrofit blends.

Automotive air conditioning

The accelerated phaseout of CFCs has brought about a corresponding acceleration in the introduction of HFC-134a in new vehicles to the extent that full conversion in the developed countries was completed during 1994. Accelerated phaseout also created the need to address retrofitting existing CFC-12 vehicles (in the order of 290 million worldwide). This report deals principally with the technology and costs associated with servicing CFC-12 vehicles in the face of a dwindling CFC-12 supply and includes information from (and recommendations for), both developed and developing countries.

OEM vehicle manufacturers unanimously selected HFC-134a as their recommended retrofit refrigerant, although other refrigerants may exist and find use in the global marketplace. Refrigerants other than HFC-134a have not been supported by vehicle OEM's for several reasons: (1) they offer no advantage over HFC-134a; (2) there is essentially no time to adequately test and commercialise additional refrigerants; (3) they create the need for all service outlets to purchase yet another set of tools and equipment; and (4) they represent additional refrigerants with which the service industry must deal, thereby posing the real threat of contaminating existing CFC-12 and HFC-134a supplies, service equipment and MAC systems. The notion that a "drop-in" refrigerant may one day magically appear is not realistic and may even delay the application of retrofit technology currently developed while users wait for such a refrigerant to appear in the marketplace.

Refrigerant availability in any given use sector is difficult to forecast. Historically, the mobile air conditioning service industry has required a significant amount of refrigerant, which it will continue to require until the fleet is retrofitted or no longer in service. The CFC production phaseout will likely find those service industries requiring CFC-12 competing for the same limited supply.

Developing cost-effective and timely retrofit technology is a formidable task. A least-cost incremental retrofit is estimated to be about US $ 120.-. Higher cost scenarios, involving additional component replacements and/or additions are likely to be necessary for a significant percentage of vehicles to maintain acceptable durability and/or performance. It should be emphasised that these costs are exclusive of, and in addition to, the cost of repairing the problems that originally brought the system in for service. These repairs are estimated to average US $ 260. MAC system manufacturers and component suppliers are expected to provide retrofit information and components to the service industry in a timely manner.

Recycling CFC-12 and HFC-134a at the job site is a currently available technology and is a reality in many developed countries, and should be encouraged globally. The value of refrigerant recycling and proper servicing cannot be over-emphasised. The "gas-and-go" type of service, wherein leaks are not repaired and refrigerant is vented directly to the atmosphere during service, must be eliminated. Technicians that repair MAC systems should be technically qualified in basic diagnostic and servicing procedures.

The Society of Automotive Engineers (SAE) has developed technical documents covering equipment requirements for containment and recycling refrigerants used in mobile A/C systems. SAE documents also include technician service and retrofit procedures that can provide guidance for Article 5(1) countries.

AFEAS and the US. Department of Energy has recently collaborated on evaluating the technology status of carbon dioxide, zeolite/water, the air cycle, and Stirling cycle for potential use in mobile A/C systems. These technologies are currently in their infancy and face significant technical hurdles which must be overcome before they can be considered to be commercialisable.

Heat pumps (heating only and heat recovery)

Heating-only heat pumps are used for space and water heating in residential, commercial/institutional and industrial buildings. In industry, heat pumps are used for heating of process streams, heat recovery and hot water/steam production. They are often an integrated part of industrial processes, such as drying, evaporative concentration and distillation. Virtually all heating-only heat pumps are electric closed-cycle compression type systems.

The vast majority of heating-only heat pumps in buildings are located in Western Europe, as most heat pump installations in Japan, USA and Canada are reversible airconditioners. It is estimated that the total number of heating-only heat pumps in these market sectors (including district heating) is roughly 1.4 million units, with a total heating capacity of about 11,000 MW and an annual heat supply of 25 TWh/year. The corresponding figures for industrial heat pumps are 7,000 units, 2,500 MW and 12 TWh/year.

HCFCs are generally accepted as a part of the solution for a rapid CFC phaseout, and HCFC-22 is the most important refrigerant in this category. Many European countries are discussing regulations on HCFCs with a view to phasing them out more rapidly than has already been agreed under the Montreal Protocol. (e.g., Germany, Sweden and maybe Italy will ban the use of HCFCs in new equipment from the year 2000).

HFC-134a is currently applied for retrofitting of existing heat pumps using CFC-12 and for charging of new installations. HFC-134a heat pump technology is considered fully mature for new systems. The demand for HFC-134a is expected to increase substantially in the next years. Moreover, other HFCs as well as HFC blends are expected to be available towards the end of the decade, thus resulting in a further increase in HFC consumption.

Ammonia has recently seen an increasing number of experimental applications for large capacity heat pump systems in Europe. Halt in CFC production and further technology development are expected to accelerate its commercialisation and market penetration in Europe, as well as in Japan and the United States. Ammonia technology for small capacity heat pumps is expected to be available by the turn of the century.

Propane is currently used in experimental -residential- heat pumps in Europe. Technology development and improved safety measures are assumed to reduce safety hazards and improve public acceptability. Hence, propane, other hydrocarbons as well as hydrocarbon blends are expected to play an increasingly important role in the mid to long term, especially in small and medium capacity heat pumps.

Carbon dioxide is a promising long-term natural refrigerant, but is not expected to become of much commercial importance until the late 1990s.

Heat pumps for heating only purposes have a negligible impact on total refrigerant consumption volumes world-wide (<1%). The estimated refrigerant volume is approximately 11,000 tonnes, with 60% CFCs and 40% HCFCs (1993). Assessments indicate that the total annual refrigerant demand for heat pumps will be about 2,300 tonnes in the year 2000, of which 70-80% are HFCs and the rest HCFCs and "natural refrigerants".

If 60% of the refrigerants in scrapped and retrofitted equipment can be recovered, approximately 2,300 tonnes of CFC and 1,150 tonnes of HCFC will be made available for reuse between the year 1995 and 2000. This is about 20% more than the expected demand for CFCs for servicing of existing heat pump installations.

Refrigerant conservation

Until a few years ago, refrigerant conservation was considered to be important only for proper system functioning. Venting refrigerants during service was a usual practice. The ozone layer depletion and the need to limit environmental effect of refrigerant emission changed this. As well, the 1991 revision of the Montreal Protocol that included a phaseout schedule for HCFC refrigerants extended the interest of conservation. To avoid any direct impact of refrigerants on environment through their emission, refrigerant conservation is a major consideration in refrigerating system design, installation, and service. Conservation deals also with the needs for servicing existing equipment for both developed and Article 5(1) countries.

As the most direct way to reduce emissions to the atmosphere, refrigerant conservation should be promoted by governments which are Parties to the Protocol. Tools may include research and development, information dissemination, financial incentives, and direct regulations. **It should start, anyhow, with regulations making recovery compulsory. Without this basic regulation, experience shows that refrigerant recovery will not be carried out.**

Refrigerant conservation has three basic elements:

- to properly design and install new equipment so as to minimise actual or potential leaks;
- to leak-tighten existing systems so as to reduce emissions, in case of continued use of CFCs or retrofit to HCFCs or HFCs;
- to improve service practices, including recovery, permitting continued system operation with reduced need to add refrigerant.

Good service practice can significantly reduce refrigerant loss by regularly checking the systems to find and repair leaks and by recovering the refrigerant each time the system has to be opened. Training of installers, operators, and service operators is required to accomplish proper cooling system operation and containment.

Availability of recovery equipment has significantly increased over the last three years. Standards have been written in order to measure the performances of equipment, and methods have been developed to make recovery more efficient.

Refrigerant removed from a refrigerating system may be returned to the same system after recycling. It may be required that refrigerant be reclaimed before it can be reused in another system to make sure that the contaminant level is consistent with the system operation. In all cases, refrigerant reuse requires taking measures to avoid mixing refrigerants.

Refrigerant which is too contaminated for reuse will ultimately have to be destroyed. At present, high temperature incineration is about the only practical method of destroying CFC and HCFC refrigerants, but other technologies may emerge in the future.

In Article 5(1) countries, priorities should be given to maintaining systems in proper operating condition including tightening up systems by finding and repairing leaks and recovering refrigerant for reuse before servicing systems. Strong government incentives will be necessary in order to reach effectiveness.

Developing country aspects

During the last couple of years, many projects have been launched in the Article 5(1) countries. These projects cover both technology, reclaim and training projects. The effort ahead shall concentrate on training, as this subject requires highest priority. Parallel with that effort, changes to new technology, collection and reclaim of CFC, HCFC, etc. are to be continued.

It is worth noting that considerations are extremely essential on which new technology will be utilised, especially the issue of the new types of refrigerants and also the utilisation of flammable refrigerants. The background of this consideration is that if the change in technology does not correspond to a specific Article 5(1) country's situation, in relation to both the home market and export, it may result in an additional change in technology within a few years.

Further more, it is considered desirable that a more stringent legislation in the Article 5(1) countries is implemented within the fields of refrigerants, refrigerating plants and related leakage rates. This is necessary in order to complete the essential changes in refrigeration technology in a successful way.

Research co-ordination and information dissemination

This section enumerates the types of information required to ensure that the phaseout of CFCs and HCFCs proceeds in an orderly and cost effective manner, provides a discussion of where this type of information may be obtained, and provides a listing of some of the key areas in which co-operative research and developmental efforts are needed. Both short- and long-term approaches to CFC and HCFC phaseout are being developed. This section points out the importance for ensuring that available information includes a discussion of both the problems associated with the near-term ban on CFC consumption (conservation, recycling, "transitional" replacements), as well as information on long-range alternatives. It also highlights the need for information to address the needs of both Article 5(1) and developed countries.

The audience for this section includes anyone responsible for policy development and equipment replacement decisions, such as government environmental officials, equipment and refrigerant manufacturers, installation and maintenance personnel, building owners and managers, consulting engineers, and facility operators. This section emphasises the need for reliable and unbiased information that includes success stories as well as analyses of programs that have been unsuccessful.

The types of information addressed in this section include:
- basis scientific information on stratospheric ozone depletion, global warming, and the role of ozone depleting substances (ODS) in these two processes;
- data on basic refrigerant properties, as described in section 2: system engineering, and equipment design and manufacturing;
- retrofitting of existing equipment, service requirements, and training;
- regulations, and
- financing mechanisms.

The section also provides a listing of where some of this information may be obtained, from both governmental and non-governmental sources. Some of the issues associated with information dissemination are discussed in the framework of providing recommendations for how information should be compiled, formatted, catalogued, abstracted and simplified for optimal use. Finally, the section presents a listing of some sources of current research on alternative refrigerants, energy efficiency and refrigerant safety.

Historical global CFC and HCFC consumption and future demand for CFC and HCFC refrigerants

This section provides historical data for CFC use, as well as estimated data for the use of CFCs until the year 2000. Some of these data have been transferred to the UNEP Technology and Economic Assessment report; further considerations on historical and future use can be found in this report. Since it is based upon many manufacturer's and UNEP estimated data, the UNEP Technology and Economic Assessment Panel provides these data in its report for information purposes only. The Panel will deal more elaborately with estimates for future consumption of CFCs and HCFCs in its March 1995 report.

It is estimated that the use of CFCs in the developed world (excluding CEITs) has decreased from 862 kt to 302 kt over the period 1986-1993; this equals a decrease in consumption by 65%. The decrease in consumption that took place over the period 1986-1992 amounted to 55%; consumption values are 862 and 386 kt for the years 1986 and 1992, respectively. However, the global use of CFCs (by developed countries including CEITs and Article 5(1) countries) is estimated to have decreased from 1133 to 643 kt over the period 1986-1992, which is a decrease in consumption of 43%. The lower decrease is mainly due to the different consumption patterns in the CEITs and the Article 5(1) countries; in the CEITs a small reduction in consumption took place, whilst Article 5(1) countries had an estimated growth in CFC consumption over the last three years of more than 10%/year. The result is that, in the timeframe 1986-1992, the CFC consumption in the CEITs and Article 5(1) countries can be estimated as fairly constant, at a level of 250-270 kt/year.

From 1986 through 1992, the global CFC refrigerant use has decreased slightly. Consumption was reduced from a level of 250-260 kt/year in 1986 (after peaking at about 300 kt in 1988-1989) to about 230 kt/year in the years 1991-1992.

The CFC refrigerant use in the developed world (excluding CEITs) was 208 kt/year in the year 1986, which had been reduced to 130 kt/year in 1992, which represents a reduction by 38%. In a comparable timeframe (1986-1992), the use of CFC refrigerants in the CEITs and in the Article 5(1) countries essentially increased by a factor of two, from about 50 kt in the year 1986 to about 100 kt in the year 1992.

Since the decrease in the use of CFC refrigerants in the developed countries (excluding CEITs) is lower than the decrease in CFC for all uses (being 55% over the years 1986-1992), it means that the share of refrigerants in the total CFC consumption is increasing in the developed countries. For the USA, Japan, and the EU, values of 24% in 1986 and 36% in 1992 can be calculated (ratio of CFC refrigerant use to all CFC uses); preliminary figures are that the percentage has even grown to 44% in the year 1993, for the countries mentioned above.

It can reasonably be assumed that the total CFC use, and particularly the CFC refrigerant use in the CEITs and the Article 5(1) countries will be essentially equal to or greater than the consumption in the developed world (excluding CEITs) in the year 1994. It can also be estimated that the CFC refrigerant use in the Article 5(1) countries may become comparable to the use in the developed countries (excluding CEITs) by the end of the year 1994/beginning of the year 1995.

The change in the use of CFC refrigerants in certain parts of the developed world between 1986 and 1993 shows interesting figures:

- o US consumption decreased from 132 kt to 65 kt, a decrease by 50%;
- o Japanese consumption decreased from 24.3 kt to 17 kt, a decrease by 33%;
- o EU consumption increased from 29.9 kt to 35.6 kt, an increase (!) by 20%.

The significant difference in reductions in the three regional markets (US, Japan, and the EU) may be the result of the significant differences in government programs. The most aggressive efforts included: large excise taxes, "no venting" regulations, limits on supply that were below Protocol limits, as well as encouragement to use all available safe alternatives.

The global CFC refrigerant use in 1994 is estimated to be roughly 230 kt, where the decrease in the developed world is offset by an increase in other countries, which are essentially the Article 5(1) countries. Estimates are that more than 80% of this continued CFC refrigerant use is for servicing existing refrigeration equipment; with more than 50% of it in a broad application area ranging from CFC-12 based commercial equipment (food storage, perishable food dispensers) to domestic appliances, but also to large equipment for commercial food or perishable food storage.

Up to date, experience suggests that refrigerants tendered for recycle at central reclamation facilities do not contribute more than 3% to the annual refrigerant sales volume. The fact that overall refrigerant demand in several large refrigeration markets has decreased by 20 to 50% suggests that internal recovery and recycle is being practised by the engineers which are the refrigeration equipment concerned.

After 1995 all developed world new CFC production will cease. The potential world supply will in fact consist of the new production as required by Article 5(1) countries to meet their basic domestic needs. The maximum production for this purpose has been estimated at 338 kt/year, which is, in fact, more than adequate for refrigeration and air conditioning equipment serviced by CFCs 11 and 12.

In the near future, shortages of “speciality” CFCs (i.e., CFC-13, -113, -114, and -115) are likely, unless users have stockpiled larger quantities in advance of the shutdown of most of the production plants in the developed world.

CEIT countries will encounter difficulties in reducing and phasing out their needs for CFC refrigerants by 1996. The consumption of CFC refrigerants in these countries is assumed to be between 10 and 20 kt in the year 1994, and to gradually decrease over the period 1994-1998/1999.

This part of the report also provides historical data for HCFC use, as well as some estimated data for the use of HCFCs until the year 2000; this in particular for the use of HCFC-22 in refrigeration. Equal to the CFC consumption, some of these HCFC data have been transferred to the UNEP Technology and Economic Assessment report.

Non-feedstock HCFC-22 use has been in the 230 kt to 260 kt range over the last 5 year period, 1989-1993. The use of HCFC-22 as a refrigerant use has been between 205 kt to 220 kt in this period. National no-venting regulations in the U.S.A., the largest HCFC-22 market in the world, has curbed the growth in consumption of HCFC-22; it is estimated that there will be a flat or even negative growth globally since recycling and refrigerant conservation become common practice in the traditional large HCFC-22 markets, all over the world.

The consumption of other HCFCs as refrigerants (HCFC-123, -124, and also HCFC-142b) is estimated to be rather modest in the near future, which will be over the six year period 1994-2000. These HCFCs will be used for some new production (e.g. chillers), but primarily they will be used as retrofitting fluids in existing equipment. Consumption is estimated to be between 15 and 25 kt/ year during 1994-2000 in the developed countries. Consumption in the Article 5(1) countries may slightly increase this consumption figure.

Other uses for HCFCs (mainly HCFC-22, -141b, and -142b) are estimated to be about 130 kt in 1994, with a consumption between 140 and 170 kt during 1994-1998; their consumption will then gradually decrease since users will have optimised technologies that provide desired performance without the use of HCFCs.

The global demand for all HCFCs is estimated to be between 300 and 335 kt in the year 2000, which is actually comparable to the consumption in the years 1993-1994. As stated above, the use of HCFCs for refrigeration has been in the order 240-250 kt in the year 1993, and is estimated to be in the order of 200 kt in the year 2000, which is in fact a reduction in HCFC use by about 20%. While there will be a small increase in the consumption of HCFCs other than HCFC-22 over the period 1993-2000, HCFC-22 consumption is estimated to decrease from 1994 to 2000, from about 230 kt to 160-170 kt in the year 2000. Next to conservation, this will mainly be due to the use of other refrigerants (HFCs, HFC blends and non-fluorocarbons) that will replace new HCFC applications from 1994 on.

1 Introduction - Montreal Protocol process

1.1 Introduction Montreal Protocol

In 1981, in response to the growing scientific consensus that CFCs and halons would ultimately deplete the ozone layer, the United Nations Environment Program (UNEP) began negotiations to develop multilateral protection of the ozone layer. These negotiations resulted in the Vienna Convention for the Protection of the Ozone Layer, in March 1985. The Convention provided a framework for international co-operation in research, environmental monitoring and information exchange.

In September 1987, 24 nations, including the United States, Japan, the Soviet Union, the EC and country members of the European Community, signed the Montreal Protocol on Substances that Deplete the Ozone Layer. By April 1991 already, 68 nations had ratified the Protocol. These countries represent over 90 percent of the world's production of CFCs and halons. The Montreal Protocol entered into force on January 1, 1989. This international environmental agreement limited production of specified CFCs to 50 percent of 1986 levels by the year 1998 and called for a freeze in production of specified halons at 1986 levels starting in 1992.

A list of CFCs, halons and other substances controlled under the Montreal Protocol is shown in Table 1.1 (Annex A status 1987, Annex A-E status 1992).

1.2 Introduction on developments 1989-1994

Shortly after the 1987 Protocol was negotiated, new scientific evidence conclusively linked CFCs to depletion of the ozone layer and indicated that depletion had already occurred. Consequently, many countries called for further actions to protect the ozone layer by expanding and strengthening the original control provisions of the Montreal Protocol.

In June 1990, the Parties to the Montreal Protocol met in London and agreed to Protocol adjustments requiring more stringent controls on the CFCs and halons specified in the original agreement and amendments placing controls on other ozone depleting substances, including carbon tetrachloride and 1,1,1-trichloroethane. Decisions were made on the basis of three Panel reports, one on the science of ozone layer depletion, one on its effects, and a third one on technology and economics. The latter one, the Technology and Economics Assessment Panel had six Technical Options Committees that each undertook assessments of the technology available to reduce the dependence on ozone depleting substances:

(1) **Aerosols, Sterilants, and Miscellaneous Uses** Technical Options Committee
(2) **Flexible and Rigid Foams** Technical Options Committee
(3) **Halons** Technical Options Committee
(4) **Refrigeration, AC and Heat Pumps** Technical Options Committee
(5) **Solvents, Coatings and Adhesives** Technical Options Committee
(6) **Economics** Options Committee

The consequence of the London Amendment of 1990 is shown in Table 1.2.

Table 1.1 Substances controlled by the Montreal Protocol, status 1994 (ODP values relative to CFC-11)

Annex A

Group I		ODP
CFC-11	Trichlorofluoromethane	1.00
CFC-12	Dichlorodifluoromethane	1.00
CFC-113	1,1,2-Trichloro-1,2,2-trifluoroethane	0.82
CFC-114	1,2-Dichlorotetrafluoroethane	0.76
CFC-115	Chloropentafluoroethane	0.43
Group II		
Halon 1211	Bromochlorodifluoromethane	3.0
Halon 1301	Bromotrifluorometahne	10.0
Halon 2402	Dibromotetrafluoroethane	6.0

Annex B

Group I		
CFC-13	Chlorotrifluoromethane	1.00
CFC-111	Pentachlorofluoroethane	1.00
CFC-112	Tetrachlordifluoroethane	1.00
CFC-211	Heptachlorofluoropropane	1.00
CFC-212	Hexachlorodifluoropropane	1.00
CFC-213	Pentachlorotrifluoropropane	1.00
CFC-214	Tetrachlorotetrafluoropropane	1.00
CFC-215	Trichloropentafluoropropane	1.00
CFC-216	Dichlorohexafluoropropane	1.00
CFC-217	Chloroheptafluoropropane	1.00
Group II		
CCl_4	Carbon Tetrachloride (Tetrachloromethane)	1.11
Group III		
1,1,1-Trichloroethane	Methyl Chloroform (1,1,1-Trichloroethane)	0.11

Annex C

Group I

Partially halogenated fluorocarbons (including HCFC-22, HCFC-123, and HCFC-141b), all with ODPs of less than 0.12, are defined as transitional substances by the Montreal Protocol under Annex C.

Group II

Hydrobromofluorcarbons

Annex E

MeBr	**Methyl Bromide**	**0.7**

Table 1.2 The London Amendment to the Montreal Protocol

Annex A - Group I
Chlorofluorocarbons: CFC-11, CFC-12, CFC-113, CFC-114 and CFC-115
(reference level: 1986)
Freeze by July 1989

20 % reduction by	January 1, **1993**
50 % reduction by	January 1, **1995**
85 % reduction by	January 1, **1997**
100 % reduction by	January 1, **2000**

Annex A - Group II
Halons: halon 1211, halon 1301 and halon 2402 (reference level: 1986)

Freeze by July 1992

50 % reduction by	January 1, **1995**
100 % reduction by	January 1, **2000**

(with possible exemptions for essential uses)

Annex B - Group I
Other fully halogenated CFCs
CFC-13, CFC-111, -112, -211, -212, -213, -214, -215, -216, and CFC-217
(reference level: 1986)

Freeze at July 1992

20 % reduction by	January 1, **1993**
85 % reduction by	January 1, **1997**
100 % reduction by	January 1, **2000**

Annex B - Group II
Carbon Tetrachloride (reference level: 1989)

Freeze at 1989 levels by July 1992

85 % reduction by	January 1, **1995**
100 % reduction by	January 1, **2000**

Annex B - Group III
1,1,1-trichloroethane (reference level: 1989)

Freeze at by January 1993

30 % reduction by	January 1, **1995**
70 % reduction by	January 1, **2000**
100 % reduction by	January 1, **2005**

Annex C - Transitional Substances
Partially halogenated fluorocarbons

Resolution calling for use only where other alternatives are not feasible with phaseout by 2020 if feasible, and no later than 2040.

Table 1.3 The Copenhagen Amendment to the Montreal Protocol
(Entered into Force June 14, 1994)

Annex A - Group I
Chlorofluorocarbons: CFC-11, -12, -113, -114 and CFC-115 (reference level: 1986)

75 % reduction by	January 1, 1994
100 % reduction by	January 1, 1996

Annex A - Group II
Halons: halon 1211, halon 1301 and halon 2402 (reference level: 1986)

100 % reduction by (with possible exemptions for essential uses)	January 1, 1994

Annex B - Group I
Other fully halogenated CFCs
CFC-13, -111, -112, -211, -212, -213, -214, -215, -216, -217 (reference level: 1986)
Freeze at 1986 levels by July 1992

85 % reduction by	January 1, 1994
100 % reduction by	January 1, 1996

Annex B - Group II
Carbon Tetrachloride (reference level: 1989)

85 % reduction by	January 1, 1994
100 % reduction by	January 1, 1996

Annex B - Group III
1,1,1-trichloroethane (reference level: 1989)

50 % reduction from 1989 levels by	January 1, 1994
100 % reduction from 1989 levels by	January 1, 1996

Annex C - Group I
HCFCs (reference level: 1989)
3.1% of the 1989 CFC ODP Consumption
PLUS the calculated level of the 1989 HCFC Consumption

Freeze by January 1, 1996

35 % reduction from base allowable level by	January 1, 2004
65 % reduction from base allowable level by	January 1, 2010
90 % reduction from base allowable level by	January 1, 2015
99.5 % reduction from base allowable level by	January 1, 2020
100 % reduction from base allowable level by	January 1, 2030

Annex C, Group II
HBFCs
100 % reduction by 1996

Annex E
Methyl Bromide
Freeze at 1991 levels by January 1, 1995

In London, a new assessment was decided, which was endorsed during the Meeting of the Parties in Nairobi, 1991 (Decision III/12). In 1991, the Assessment Panels and the TOCs performed substantial effort to collect information for a new assessment. In this effort, the TOC Refrigeration, AC and Heat Pumps conceived a section in its report that dealt with estimates for the consumption of CFCs, HCFCs and HFCs in the near future.
In an extra effort to assess the consequence of ozone layer depletion from anthropogenic emissions of methylbromide, an interim Technical Committee reported on science and technology in 1992. Based upon all information available, the Parties decided on new phasedown schedules for the different controlled substances, and methyl bromide was introduced as a controlled substance. The consequence of the Copenhagen Amendment is shown in Table 1.3.

The Parties in Copenhagen took a number of decisions which concern the work of the Technology and Economic Assessment Panel and its Committees. Decision IV/13, on "Progress": *(2) To request the Technology and Economics Assessment Panel and its Technical and Economics Options Committees to report annually to the OEWG of the Parties to the Montreal Protocol the technical progress in reducing the use and emissions of controlled substances and assess the use of alternatives, particularly their direct and indirect global warming effects.*
In 1993 and 1994, therefore, the Technology and Economic Assessment Panel issued a progress report on the technical progress in reducing the use and emissions of controlled substances. In 1994, next to the technical progress, the report, amongst others, contained information on essential use recommendations, on recovery and recycling, on inadvertent losses during production and handling, and also on HCFCs. This according to decision IV/30, "HCFCs": *(a) to evaluate alternative substances and technologies to the application for HCFCs as refrigerant and as insulation gas in rigid foam; (b) to identify other applications for HCFCs, if any, where other more environmentally suitable alternatives or technologies are not available.*

The Parties also decided a new assessment to be carried out in 1994 according to Decision IV/13, "Assessment reports" :
(3) To request the three assessment panels to update their reports and submit them to the secretariat by 30 November 1994 for consideration by the OEWG and by the seventh meeting of the Parties to the Montreal Protocol. These assessments should cover all major facets discussed in the 1991 assessments with enhanced emphasis on methyl bromide. The scientific assessment should also include an evaluation of the impact of subsonic aircraft on ozone;
(4) To encourage the panels to meet once a year to enable the cochairpersons....

They also decided that the Technology and Economic Assessment Panel should investigate the feasibility of a control schedule for HCFCs in the Article 5(1) paragraph 1 countries, according to Decision V/19, "Control measures to be applicable to Parties operating under paragraph 1 of Article 5(1) with respect to the controlled substances in Groups I and II of Annex C and under Annex E" :
(1) To request the Scientific Assessment Panel and the Technology and Economics Assessment Panel to assess the following in accordance with Article 6 of the Protocol and to submit their combined report, through the Secretariat, by 30 November at the latest, to the Seventh Meeting of the Parties:
(a) what base year, initial levels, control schedules and phaseout date for consumption of controlled substances in Group I of Annex C are feasible for application to Parties operating under paragraph 1 of Article 5;
(b) what base year, initial levels, control schedules and phaseout date for consumption of controlled substances in Group II of Annex C are feasible for application to Parties operating under paragraph 1 of Article 5;

(c) what base year, initial levels, control schedules and phaseout date for consumption of controlled substances in Annex E are feasible for application to Parties operating under paragraph 1 of Article 5;
(2) To request the OEWG to consider....

The Parties in Copenhagen also considered the operation of the Interim Multilateral Fund, which was decided in London, 1990. From that moment, the Multilateral Fund started its operation and its Executive Committee considered country programmes, work programmes for the implementing agencies involved (UNEP, UNDP, UNIDO and the World Bank) and specific project proposals for approval. By the end of 1994, a large number of country programmes and project proposals had been approved, and several strategic policy decisions had been taken. Projects deal with all the application sectors of controlled substances in a large number of Article 5(1) paragraph 1 countries. An important part is formed by projects that deal with the conversion from CFCs to substitutes in the refrigeration circuit and in foams of domestic refrigerators. In order to analyse technologies for implementation, the World Bank decided to install an advisory group in 1992, the Ozone Operation Resource Group (OORG). Under the chairmanship of several of its members, working groups derived a number of recommendations for the implementation of projects. Where it concerns refrigeration, the latest recommendations for foams and refrigerants in household refrigerators were published in May 1994, recommendations for the conversion of chillers were published in August 1994.

The present status (November 1994) is that the Montreal Protocol has been ratified by 142 countries, Parties to the Protocol. The London Amendment has been ratified by 96 Parties and the Copenhagen Amendment has been ratified by 35 Parties and has entered into force June 1994.

1.3 UNEP Assessment Panels

The 1992 Copenhagen Meeting of the Parties to the Montreal Protocol reconvened the 1991 UNEP Assessment Panels, which consisted of the Scientific, Environmental Effects and Technology and Economics Assessment Panels. The three international panels should report on:

- the scientific findings and observations regarding stratospheric ozone depletion and related phenomena and issues (e.g. Ozone Depletion and Global Warming Potentials);
- the environmental and public health effects of stratospheric ozone depletion;
- the technical feasibility and earliest possible date in each of the major use sectors, of reducing emissions and phasing out production and consumption of controlled (ozone depleting) substances and the related anticipated economic concerns.

The 1994 Technical and Economic Assessment study has been carried out by the Technology and Economic Assessment Panel and its seven Options Committees. The seven Committees (the six committees mentioned under 1.2, plus the Methyl Bromide Technical Options Committee) consisted of more than 300 experts from a large number of countries (for a list see the Technology and Economic Assessment Panel Report 1994). The 1994 Options Committees consist of some members of the 1989 and 1991 Committees and additional new experts, to provide the widest possible international participation in the review. Experts from industry, government, academic institutions and non-government organisations were invited to prepare comprehensive and technically specific "Options Reports". UNEP staff, Technical and Economics Panel Chairpersons and the Technical Options Committee Chairs and Cochairs contacted producers, equipment manufacturers, trade associations, users, research institutions, standards making organisations and others to arrange for comprehensive technical input.

The Options Committee reports have been subject to a peer review before final release. The final version of the reports will be distributed internationally by UNEP.

The Options Committee reports form part of the UNEP review under Article 6 of the Montreal Protocol. Article 6 specifically directs Parties (nations that have ratified the Protocol) to assess whether the control measures, as provided for in Article 2 of the Protocol, are sufficient to meet the goals for reducing ozone depletion based on a review of the current state of knowledge on technical, scientific, environmental and economic issues related to stratospheric ozone protection.

This Technical Options Report on Refrigeration, AC and Heat Pumps is part of the work of the Technology and Economic Assessment Panel under Decision IV/13. The information collected will also be part of the Technology and Economic Assessment Report 1994. This report, as well as the reports of the two Panels on Science and Environmental Effects, will be considered by the Parties for further decisions to be taken at their 7th Meeting in Vienna, 1995.

Technological and economic measures to reduce the dependence on ozone depleting substances will be considered against the background of the 1994 findings of the Scientific Assessment Panel (consisting of 226 of the world's leading atmospheric science experts). An executive summary of recent major findings and observations was already published in September 1994 and contains, amongst others, the following paragraphs (in abbreviated form, compare the Scientific Assessment Panel Report, UNEP/WMO, 1994):

- *The atmospheric growth rate of several major ozone depleting substances have slowed, demonstrating the expected impact of the Montreal protocol and its Amendments and Adjustments......*Peak total chlorine/bromine loading in the troposphere is expected to occur in 1994, but the stratospheric abundance's of chlorine and bromine are expected to continue to grow for a few more years, increasing global ozone losses are predicted (other things being equal) for the remainder of the decade, with gradual recovery in the 21st century.
- *The atmospheric abundance's of several of the CFC substitutes are increasing, as anticipated.* With phaseout dates for the CFCs and other ozone depleting substances now fixed by international agreements, several hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs) are being manufactured and used as substitutes. The atmospheric growth of some of these compounds (e.g. HCFC-22) has been observed for several years, and the growth rate of others (e.g., HCFC-142b and HCFC-141b) are now being monitored. Tropospheric chlorine in HCFCs increased by 5 ppt/year in 1989 and about 10 ppt/year in 1992.
- *Record low global ozone levels were measured over the last two years.* Anomalous ozone decreases were observed in the mid latitudes of both hemispheres in 1992 and 1993. The Northern Hemisphere decreases were larger than those in the Southern hemisphere. Globally, ozone values were 1-2% lower than would be expected from an extrapolation of the trend prior to 1991, allowing for solar-cycle and quasibiannual-oscillation (QBO) effects. The 1994 global ozone levels are returning to values closer to those expected from the longer-term downward trend.
- *The conclusion that anthropogenic chlorine and bromine compounds, coupled with surface chemistry on natural polar stratospheric particles, are the cause of polar ozone depletion has been further strengthened.*
- *The Antarctic ozone "holes" of 1992 and 1993 were the most severe on record.*
- *Ozone losses have been detected in the Arctic winter stratosphere, and their links to halogen chemistry have been established.*
- *Stratospheric ozone losses cause a global-mean negative radiative forcing.........*Calculations indicate that, on a global mean, the ozone losses between 1980 and 1990 offset about 20% of the radiative forcing due to the well mixed

greenhouse-gas increases during that period (i.e. carbon dioxide, methane, nitrous oxide and halocarbons).

The Scientific Assessment Report also deals with six "Implications For Policy Formulation", which are quoted here (including the full text of one of the implications, see for full information the Scientific Assessment Report, UNEP/WMO 1994):

- *The Montreal Protocol and its Amendments and Adjustments are reducing the impact of anthropogenic halocarbons on the ozone layer and should eventually eliminate this ozone depletion.*
- *Peak global ozone losses are expected to occur during the next several years.*
- *Approaches to lowering stratospheric chlorine and bromine abundance's are limited.* Further controls on ozone-depleting substances would not be expected to significantly change the timing or the magnitude of the peak stratospheric halocarbon abundance's and hence peak ozone loss. However, there are four approaches that would steepen the initial fall from the peak halocarbon levels in the early decades of the next century:

(i) If emissions of methyl bromide from agricultural, structural and industrial activities were to be eliminated in the year 2001, then the integrated effective future chlorine loading above the 1980 level (which is related to the cumulative future loss of ozone) is predicted to be 13% less over the next 50 years relative to full compliance to the Amendments and Adjustments to the Protocol.

(ii) If emissions of HCFCs were to be totally eliminated by the year 2004, then the integrated effective future loading above the 1980 level is predicted to be 5% less over the next 50 years relative to full compliance to the Amendments and Adjustments to the Protocol.

(iii) If halons presently contained in existing equipment were never released to the atmosphere, then the integrated effective future loading above the 1980 level is predicted to be 10% less over the next 50 years relative to full compliance to the Amendments and Adjustments to the Protocol.

(iv) If CFCs presently contained in existing equipment were never released to the atmosphere, then the integrated effective future loading above the 1980 level is predicted to be 3% less over the next 50 years relative to full compliance to the Amendments and Adjustments to the Protocol.

- *Failure to adhere to the international agreements will delay recovery of the ozone layer.*
- *Many of the substitutes for the CFCs and halons are also notable greenhouse gases.*
- *Consideration of the ozone change will be one necessary ingredient in understanding climate change.*

1.4 Terms of reference for the Refrigeration Committee

The Technical Options Report on Refrigeration, AC and Heat Pumps has been drafted in the form of a number of sections (one section on thermodynamic data, eight sections on application areas, and sections on refrigerant conservation, developing countries, information dissemination and refrigerant consumption). The structure was chosen similar to the structure of the 1991 Options Committee report.

Each of the sections consisted of 6-12 experts in the specific sector, chaired by one or two experts who did the larger part of the drafting and the co-ordination within the section. The Committee included representatives from African, Asian, Australian, European, Latin and North American governments and companies (see Table 1.4).

Table 1.4 "Member countries" of UNEP's Refrigeration, AC and Heat Pumps Committee

Austria
Belgium
Brazil
Canada
China, PR
Denmark
France
Germany
India
Italy
Japan
Kenya
Malaysia
Netherlands
New Zealand
Norway
Saudi Arabia
Sweden
Switzerland
Thailand
United Kingdom
United States

Each of the sections consisted of 6-12 experts in the specific sector, chaired by one or two experts who did the larger part of the drafting and the co-ordination within the section. The Committee included representatives from African, Asian, Australian, European, Latin and North American governments and companies (see Table 1.4). Affiliations of the Committee members are listed in Table 1.5 (about 100 organisations were involved in the drafting of the report). The names of all the experts are given in Annex II to this Options Report.
Several drafts of the report were made, reviewed by the separate sections and discussed in Options Committee meetings (draft End 1993, draft May 1994, draft July 1994, peer review draft September 1994 and final report November 1994). Committee meetings were held in Germany (Hannover), Italy (Padova), the Netherlands (Maastricht), and the United States (Washington D.C., twice, and Purdue University, Indiana).

As stated, the structure of the 1994 Refrigeration Techical Options Committee Report is similar to the one of the Options Report 1991, except for the fact that the report contains more data on the global consumption of controlled substances over the period 1986-1993, and some estimates concerning the future global consumption of controlled substances in specific refrigeration, AC and heat pumps sectors. With technology proceeding rapidly the report is no simple update of the 1991 report, but all options described in 1991 are re-examined taking into account the present range of technological developments.

Next to the section on "Refrigerant conservation", the report contains two more general sections. One carries the title "Developing country aspects" and deals with specific problems and actions required in Article 5(1) countries. A second one examines the dissemination of information and the need for research co-ordination. This section has been conceived in order to stimulate acceleration of the conversion process on a global scale; it contains an extensive list with contact addresses for information. All sections describing application areas of controlled substances consider the feasibility of options in new and existing equipment (e.g. retrofits), give specific information on the need for fluorocarbons (HCFCs and HFCs), and consider the potential of recovery and recycling.

The report has been peer reviewed by a large number of institutions and associations, each of them reviewing the different sections in a co-ordinated effort in a tight time frame (see Table 1.6).

Table 1.5 Organisations whose employees served on the 1994 UNEP TOC Refrigeration

Adtec Services Ltd.	L&E Teknik og Management
Allied Signal Inc.	Lloyds Register of Shipping
Americold Corp.	Lyngby Tech University, Refr.Lab.
ARI, Air Conditg and Refr. Institute	Matsushita Electric Ind. Ltd
Assoc. Eur des Exploit Frigor AEEF	Matsushita Refr. Co
Battelle Pacific Northwest Labs	Meat Industry Research Inst NZ
Behr GmbH	Ministry of Defence UK
Calm (Consultant)	MITI Japan
Caneta Research Inc.	Mitsubishi Heavy Industries
Carrier Co.	Nairobi University, Mech. Eng.
Carrier Transicold	Nat. Chemical Laboratory Pune
Chalmers University of Technology	NIST, Nat. Inst. Stand. Technology Boulder
Copeland Co.	NIST, Nat. Inst. Stand. Technology Gaithersburg
Daikin Industries Ltd.	Nippondenso Co.
Danfoss GmbH	Oak Ridge Natl Laboratory ORNL
Dehon Service SA	Ober-Oesterreichische Kraftwerke AG
Dunham Bush Inc.	Ozone Committee Saudi Arabia
DuPont de Nemours, E.I.	Politecnico di Milano, Eng. Dept.
EA Technology Capenhurst	Re / genT Co
Ecole des Mines Paris	Remco Ltd.
Elf Atochem France	Robinair Division, SPX Div.
Elf-Atochem North America	Sabroe Refrigeration A/A
Embraco SA	Sanden AC
Environment Canada	Sanyo Electric Co.
Fisher and Paykel, Refr. Div.	Schatten N.V./SA
FKW GmbH Hannover	Sea Containers Ltd.
Frigoscandia	SINTEF, Div. Ref. Engineering
Gas Research Institute Chicago	Societe Trane France
Gas Cooling Center	SRCRA Cambridge
General Electric, Appliance Div.	Star Refrigeration Ltd.
Gen. Mach. Res. Inst. GMRI, Hefei	Sulzer Friotherm Ltd.
Gilkey (Consultant)	Sun Test Engineering
Harrison Division of General Motors	Technical University Eindhoven
Haukas (Consultant)	The Trane Company
Heat Pump Tech Center Tokyo	Toshiba Co.
Hoechst AG	Tsing Hua University, Dept. Mech. Eng
Hussman Co.	Unite Hermetique SA
IEA Heat Pump Centre	Unitor Ships Service
Indian Inst. Technology IIT Bombay	University of Hannover, Refr. Engineering
Indian Inst. Technology IIT New Delhi	University of Hannover, Thermodynamics
Inform. Centre Refr Heat Pumps Karlsruhe	U.S. Environmental Protection Agency
Integral Technologie Flensburg	Valeo Thermique
Int. Institute of Refrigeration IIR	Vilter Manufacturing Co.
Int. Institute of Ammonia Refrigeration IIAR	Whirlpool Italia M&T Refr Deptmt
Japanese Refr and AC Ind Ass JRAIA	World Bank
Japanese Refrigeration Association	WS Atkins Energy Ltd.
Keio University, Mech. Engineering	Xi'an Jiatong Univ. Dept Power Machinery
Kelvinator of India Ltd.	York Int. Co
LGN Energikonsult	

Table 1.6 ***Organisations contacted for the peer review of the UNEP TOC Refrigeration Report***

AFEAS	Alternative Fluorocarbon Environmental Acceptability Study
AFF	French Association of Refrigeration
ARI	Air Conditioning and Refrigeration Institute
ASERCOM	European Association of Compressor Manufacturers
ASHRAE	American Soc. of Heating, Refrigeration and Air Conditioning Engineers
BIR	British Institute of Refrigeration
BRA	British Refrigeration Association
CECOMAF	European Refrigeration Equipment Manufacturers
DKV	German Refrigeration Society
EnCan	Environment Canada
FOE	Friends of the Earth International
Greenpeace	Greenpeace International
IIAR	International Institute of Ammonia Refrigeration
IIR	International Institute of Refrigeration
JRAIA	Japanese Refrigeration and Air Conditioning Industry Association
MVMA	Motor Vehicles Manufacturers Association
ZVEI	German Refrigerator Manufacturer Association

1.5 Refrigeration, air conditioning and heat pumps

1.5.1 General remarks

With a decreasing use of CFCs, especially in aerosols, foams, solvents and miscellaneous uses, and a less rapid decline in the use of CFCs for refrigeration (see section 15), the percentage of the total CFC consumption for refrigeration has been steadily increasing over the period 1986-1993. The economic impact of refrigeration technology is much more significant than generally believed. While the yearly investment in machinery and equipment may approach $100,000 million, the value of the products treated by refrigeration will be ten times this amount. This is one of the reasons that economic impacts of the phaseout of CFCs and HCFCs are difficult to estimate. It is clear that investment in technology using CFCs should be avoided anyhow, investment in HCFC technology should be subject to strategic considerations on the availability of HCFCs, emissions and economic aspects of equipment operation.
The future of mankind, and his food supply in particular, depends on the availability of sufficient energy and on the availability of efficient refrigeration methods. Of course, this aspect must be more than balanced by a concern for the conservation of the biosphere, including in particular the global warming effect. Energy efficiency, therefore, is one of the most important aspects. In all application sectors described in this report, most of the attention is focused on the vapour compression cycle. This cycle has so far provided the most simple, economic and efficient way for refrigeration (this includes cycles for fluorocarbons, ammonia and hydrocarbons).

As an implementing agency for conversion investment projects in domestic refrigeration in the developing countries, the World Bank uses a number of recommendations, derived by its OORG advisory group. Although there are differences in the investments for different types of refrigerants, they illustrate the importance of the vapour compression cycle in the conversion, whether on fluoro- or hydrocarbons:

- Good practice, recovery and recycling, adequate servicing and maintenance practices, supporting infrastructure and training projects should be considered for implementation as a first priority in all refrigeration and air conditioning sectors. Recovery should be associated with effective arrangements for recycling or reclamation.
- HFC-134a is a recommended alternative for all CFC-12 based domestic refrigerator/freezer applications. Effective HFC-134a technology transfer is of utmost importance and should be within the framework of existing working relationships or agreements with technology suppliers established for this purpose.
- Isobutane is a recommended alternative for a large part of the CFC-12 domestic refrigerator/freezer applications. Safety issues currently preclude applications such as automatic defrost appliances and cost effectiveness is adversely affected if a range of safety design features are necessary. Cost effectiveness compared to other options varies from comparable to much lower, depending on costs for compressor conversion and safety design features. Isobutane technology transfer is conditional on the support of a technology developing partner experienced in the production of comparable refrigerator/freezer for the commercial market. It is recommended that project documentation should require a signed agreement by the technology partner (at the time of bidding) that it will provide assurances on safety issues to the enterprise and these are considered to be adequate by the implementing agency and the OORG reviewer.
- Blends containing HCFCs do not constitute a final solution to ODS phaseout in domestic refrigerator/ freezer applications. Technology transfer opportunities are also limited due to lack of experience/ use in developed countries. Also, given the anticipated difficulties in servicing such equipment, the use of such blends should be considered only in cases where country specific circumstances warrant them.
- HFC-152a is a viable alternative and its use can be recommended in circumstances where suppliers or institutions experienced in the critical issues associated with the HFC-152a technology are available. Since it is a flammable fluid, its use will require analogous constraints and incorporation of safety design features as discussed under paragraph 3.
- Conversion to HFC or isobutane based new refrigeration equipment in a developing country should be phased, with the first phase encompassing pilot production, with emphasis on reliability. Conversion to alternative refrigerant technology should automatically imply critical assessment as to the impact on the energy efficiency of the equipment.

1.5.2 Energy efficiency

Next to ozone depletion, global warming is the main issue governing the selection of refrigerant chemicals for the near- mid- and long-term. In all energy related uses, the relation between the CO2 produced in electricity generation (to operate the product) and the direct global warming of the substitute chemical have to be taken into account. This was already described in the 1989 Refrigeration report, and, more extensively, in the 1991 Options report. AFEAS, the Alternative Fluorocarbon Environmental Acceptability Study, cosponsored by the US Department of Energy, conducted a study in 1990/91 into the importance of the global warming potential of substitutes compared to the efficiency in the operation of energy related applications (the total equivalent warming impact, TEWI); the summary of this report was attached to the 1991 Options report.
Although it does not form a direct issue within the framework of the Montreal Protocol, consideration on energy efficiency and direct global warming should play an important role in the selection of future chemicals. Options for energy efficient operation form an important issue in each of the sections of the Refrigeration report.

AFEAS, again cosponsored by the U.S. Department of Energy, conducted a study "Energy and global warming impacts of not-in-kind and next generation CFC and HCFC alternatives" and will publish a report in 1994/95. Particularly, alternative chemicals and technologies are considered as substitutes for CFCs, HCFCs, and the use of the vapour compression cycle for refrigeration and air conditioning. Among these alternatives are:

- HFCs with a zero ODP for use in conventional vapour compression cycles;
- Hydrocarbons and CO2 vapour compression cycles;
- Ammonia compression systems;
- Water based vapour compression systems;
- Air cycle and thermoacoustic compression systems;
- Stirling cycle refrigeration;
- Absorption and adsorption heat pumping and/or refrigeration cycles;
- Magnetic and thermoelectric refrigeration.

The AFEAS report examines the 1994 status of each of these technologies and their potential as alternatives to the existing technologies based on CFCs and HCFCs. In addition, the report contains an evaluation of the total equivalent warming impacts (TEWI) for those alternative technologies which are close enough to commercialisation that performance data are available. AFEAS also conducted two workshops on non-fluorocarbon technologies which were held in 1993 (Breckenridge, USA and Wiesbaden, Germany) and were chaired by independent panels of experts. One of the observations from these workshops was that the vapour compression cycle -using environmentally acceptable alternatives- still has the best long-term promise for energy efficiency. Reports on the above technologies will be available from the AFEAS organisation in 1995.

A preliminary summary on these technologies, as made up by small number of TOC members, is attached to this report as Annex I.

1.5.3 HCFCs

Alternatives to HCFCs are becoming commercially available. Blends of HFCs are often propagated as the (long term) substitutes; this certainly holds for existing equipment and retrofit procedures. For new equipment, non-fluorocarbon cycles may also form an alternative in selected cases. Information can be found in the different sections of this report.

However, a rational approach to freeze and phaseout the production of HCFCs, as transitional chemicals, should allow a minimum time period to permit the industry to develop and commercialise alternatives (which is underway), and should further allow a rational phasing in of new (i.e. replacements for the transitional chemical equipment) equipment in order to avoid high obsolescence costs. This particularly relates to the servicing of existing equipment. Too early or premature measures to phaseout transitional chemicals could be counterproductive, since there will be no incentive for refrigeration equipment manufacturers to invest in HCFC technology and for a large numbers of users to change away from CFCs. In particular the necessary incentives should be provided to Article 5(1) countries to transition as soon as possible from CFCs.

The above is in particular valid for chillers. The larger part of the chillers in the world (the majority being on CFC-11) has not been retrofitted from CFCs to substitutes. The only alternative available for CFC-11 chillers is so far HCFC-123; blends cannot be used due to the frequently applied flooded evaporator systems. E.g. for CFC-chillers in the Article 5(1) countries, the World Bank OORG recommendations include the conversion to both HCFC-123 and HFC-134a.

As a conclusion, a phasedown schedule for HCFCs has to take into account many different effects. In refrigeration and air conditioning this also relates to obsolescence and long term servicing needs, in fact to confidence at the user level. While not making a recommendation for certain phaseout schedules, it will be clear that a not too stringent phaseout date combined with a low ceiling in the consumption ("cap") will be stimulating conversions more than earlier phaseout dates with a higher ceiling in consumption. This will also work out positively on the chlorine loading of the atmosphere in the 1996-2005 period.

1.5.4 Contents of this report

Section 2 presents the availability of thermodynamic data for HCFCs and HCFC replacements, sections 3 through 11 deal with the dependence or independence of each of the application sectors on HCFCs, section 12 deals with the improved containment of refrigerants in systems including recovery, and section 14 describes the ongoing research and development, including the one on HCFC alternatives.

In order to support further discussions on HCFC consumption, section 16 in this report gives the HCFC consumption over the period 1986-1993 as well as estimates regarding near future consumption levels (until the year 2000).

2 Refrigerant data

2.1 Scope

The requirements for fluids which might serve as replacements for the CFC and/or HCFC refrigerants in the vapour compression cycle are considered, and a list of candidates is presented. The focus of this section is on the thermophysical properties. Included are a discussion of the thermophysical and other properties required to evaluate a candidate refrigerant and a summary of the available data.

2.2 Overview

2.2.1 Present refrigeration equipment

2.2.1.1 Thermodynamic cycles

Refrigerants are the working fluids in refrigeration, air-conditioning, and heat pumping equipment. The great majority of such equipment operates on the vapour compression cycle. Other cycles can produce refrigeration or heat pumping. Air cycles such as the reverse Brayton cycle utilise air as both the working fluid and the cooling medium. Such cycles are often used in aircraft because of weight and space limitations. Reverse Stirling cycles employing a gaseous working fluid find use in low power applications at cryogenic temperatures. Absorption cycles replace the compressor of the vapour compression cycle with a heat-driven absorption/desorption process to generate the required pressure difference between the condenser and evaporator.

2.2.1.2 Vapour compression equipment

In the basic vapour compression cycle, heat is removed from a low temperature source (such as a refrigerated space) by the evaporation of refrigerant at low pressure within a heat exchanger; the low pressure vapour is compressed to a higher pressure by the input of mechanical work, raising the saturation temperature so that heat can be rejected to a high temperature sink (ambient air in the case of most refrigeration applications) by the condensation of refrigerant. The condensate is passed through an expansion device to reduce its pressure to that of the evaporator, completing the cycle. Modifications to the basic vapour compression cycle include additional heat exchangers to increase efficiency and the cascading of two cycles to obtain refrigeration at lower temperatures.

Despite the existence of other refrigeration cycles and their use in specialised niches, vapour compression equipment dominates in most refrigeration and heat pumping applications. This is due to the simplicity of the basic vapour compression cycle, both conceptually and in terms of the required hardware, the ability to closely approximate the theoretical cycle in practical equipment, and good efficiency, stemming, in part, from the utilisation of phase-change heat transfer processes. The remainder of this section will be limited to refrigerants for use in the vapour compression cycle.

2.2.2 Present refrigerants

The predominant refrigerants in use today for most applications are members of the halocarbon family of chemical compounds. To understand this dominance, it is necessary to examine the requirements for the ideal refrigerant. These are summarised in Table 2.1 /McL87/.

2.2.2.1 Health and safety requirements

The most essential requirement is chemical stability all the other properties would be meaningless if the fluid decomposed or reacted in use to form something else. The next most important characteristics relate to health and safety. Numerous safety codes (e.g. /ASH94/, /BSI80/) require the use of a non-flammable refrigerant with a very low order of toxicity in residential and many commercial applications. It is in these categories that the halocarbons excel over all other fluids for use in the vapour compression cycle. Indeed, it was the conviction that the success of the domestic refrigerator demanded a fluid safer than the ammonia and sulphur dioxide then in use that led to the development of the CFCs in the late 1920's /Mid37/. This means that alternative refrigerants must be very carefully investigated with respect to their toxicity, including not only acute health risks but also carcinogenic, mutagenic and teratogenic risks.

However, safety risks of the refrigerant cannot be separated from the overall safety of the equipment /Cal94a/. The design of all refrigeration systems must consider the risks associated with the chosen refrigerant. Risks can be managed in many ways, but usually at increased costs. Flammable and/or toxic refrigerants are permitted by most safety codes if they are contained within special machinery rooms. Flammable refrigerants have long been used in certain industrial processes where access is restricted to trained personnel. Small systems (such as a residential heat pump) using a flammable refrigerant could be located entirely outside, with a secondary fluid exchanging heat with the conditioned space. Ignition sources, both within the equipment (such as sparks from electrical switches) and without (for example, a nearby gas furnace), must be considered in any use of a flammable refrigerant. The risks of a flammable refrigerant can also be mitigated by using very small quantities of refrigerant. This last strategy has been important in the recent acceptance of hydrocarbons in domestic refrigerators in some countries, particularly Germany. Most refrigeration systems operate at significant pressures and must be designed as pressure vessels. Because of these factors, retrofitting any refrigerant, and particularly a flammable refrigerant, in existing equipment must be done with great care. This also holds for servicing equipment with flammable refrigerants for which manufacturers have been concentrating on the design of procedures and have started doing risk analyses.

2.2.2.2 Environmental requirements

To these traditional health and safety criteria, environmental criteria must be added. A refrigerant, if released to the atmosphere, should not contribute to stratospheric ozone depletion, tropospheric smog formation or global warming. The "natural refrigerants" (e.g. ammonia, the hydrocarbons, and carbon dioxide) generally excel in this category. The great stability of some of the halocarbons, long considered an asset, is now seen to be a liability in this regard. However, any detrimental environmental effects of a refrigerant will be mitigated by containment within the refrigeration system.

Table 2.1 Ideal refrigerant criteria

Chemical:
- *Stable and inert*

Health, Safety and Environmental:
- *Low toxicity*
- *Nonflammable*
- *Does not degrade the environment*

Thermophysical Properties:
- *Critical point and boiling point temperature appropriate for the application*
- *Low molar vapour heat capacity*
- *Low viscosity*
- *High thermal conductivity*

Miscellaneous:
- *Miscible with lubricating oil (some applications)*
- *High vapour dielectric strength*
- *Low freezing point*
- *Materials compatibility*
- *Easy leak detection*
- *Low cost*

2.2.2.3 Physical properties

The vapour compression cycle takes advantage of a change in physical state of a working fluid brought about by the application of heat and mechanical work. The salient properties characterising the physical state of a substance are its thermophysical (i.e. thermodynamic and transport) properties. Thus, to be useful as a refrigerant, the thermophysical properties of a substance must satisfy certain requirements. These properties determine not only whether a fluid is suitable for use at all as a refrigerant but also the efficiency and economy of the cycle. However, there will not be a single alternative refrigerant suitable for all uses. The search for alternative refrigerants is one for a variety of substances, each of them best satisfying the requirements and balancing the trade-offs for a particular application.

2.2.2.4 Thermodynamic properties

The thermodynamic requirements of a refrigerant in the vapour compression cycle have been considered by a number of authors, including /Ale87/, /Ang88/, /Ber86/, /McL88a/, /McL90/, and /Nar88/. While these various reports focus on different aspects and different applications, all are in essential agreement. They reveal that different aspects of the vapour compression cycle lead to different, and often contradictory, thermodynamic requirements. The most important conflict exists between the efficiency of a cycle and its heating or cooling capacity. The efficiency generally increases as the critical temperature of the refrigerant increases while the capacity decreases with increasing critical temperature. This represents an economic trade-off. The efficiency determines the operating cost while the capacity influences the capital cost of the equipment, particularly the compressor. The critical pressure also has a significant effect, with capacity increasing with increasing critical pressure. These analyses also imply that replacement fluids should be simple molecules with critical points and boiling points similar to existing fluids, at least for use in the simple vapour compression cycle. For centrifugal compressors, the capacity is inversely proportional to the square root of the refrigerant molecular weight, again favouring simple molecules. More complex molecules may be a better match for cycles incorporating intra-cycle heat exchange or other modifications /McL90/.

2.2.2.5 Transport properties

The viscosity and thermal conductivity have a large impact on the design and required size of system components, particularly the heat exchangers. Low viscosity and high thermal conductivity are desirable for refrigerants. While the halocarbons have transport properties that make them good refrigerants, other compounds, notably ammonia and simple hydrocarbons such as propane, have superior characteristics /McL88b/.

2.2.2.6 Other properties

A number of other, more practical, criteria are also necessary or, at least, desirable. Solubility and miscibility with lubricating oils and high vapour dielectric strength are important, especially for systems employing hermetic compressors. A freezing point below the lowest expected system temperature is necessary, and a means of easily detecting leaks is desirable. Compatibility with materials commonly used in refrigeration systems, including lubricating oils, seals, hoses, and motor insulation's, as well as the metals used to fabricate heat exchangers and compressors, is obviously required. While the cost of the fluid must not be exorbitant, historically the cost of the CFC refrigerants has been a tiny fraction of the total system cost, and moderate cost increases for the alternative refrigerants can be tolerated. However the use of a particular fluid must not inflict extraordinary costs for the equipment, either due to corrosion problems, high pressures, or exceptional safety precautions. The halocarbon and hydrocarbon refrigerants offer very favourable properties for this final set of criteria. Ammonia does limit the choices, but suitable materials are available.

2.2.3 Summary of present practice

In summary, there are very good reasons for the present use of halocarbon refrigerants in the vapour compression cycle. The recent acceptance of hydrocarbon refrigerants in some applications in some countries may signal a shift in the relative importance of some of the selection criteria. Many other cycles are possible (and some are currently used in specialised applications), but the vapour compression cycle offers the most efficient and economical choice for most applications. This is not likely to change because of the need to replace the ozone depleting refrigerants.

2.2.4 Refrigerant nomenclature

2.2.4.1 Numerical designation

Refrigerants are most commonly referred to by a numbering system formalised into a standard by ASHRAE /ASH92b/. This system has been accepted by the International Organisation for Standardisation /ISO74/ and as a national standard by several countries. In this system, a two- to four-digit number is used to designate the chemical formula. The right-most digit is the number of fluorine atoms in the molecule. The second digit from the right is the number of hydrogen atoms plus 1. The third digit from the right is the number of carbon atoms minus 1; this digit is omitted if 0 (i.e., single carbon). The fourth digit from the right is 1 if a carbon-carbon double bond is present; it is omitted for saturated compounds. The presence of bromine is indicated by appending B with the number of bromine atoms. Except for these indicated numbers of fluorine, hydrogen, and bromine the carbon atoms are assumed to be fully saturated with chlorine. Different isomeric forms of the same chemical formula are indicated by one or two lower case letters appended to the number. Although not within the scope of the standard, the same numbering scheme has been applied to the fluorinated ethers.

The ASHRAE standard also assigns numbers sequentially to refrigerant blends (400 series), azeotropes (500 series), miscellaneous organic compounds (600 series), and inorganic compounds (700 and 7000 series). For the 400 series blends, the number may be appended by an upper case letter; these appended letters are assigned sequentially to designate particular blend compositions which have been commercialised.

2.2.4.2 Prefix letter

In the ASHRAE and ISO standards, the number is preceded by the letter "R" (this is the most common usage), the word "Refrigerant" or a trade name. A prefix letter of "C" in conjunction with the "R" indicates a cyclic compound. In response to current usage, the ASHRAE standard /ASH92b/ allows the use of composition designating prefixes, such as CFC-12 or HFC-134a. "CFC" indicates a molecule composed of chlorine, fluorine, and carbon. "HCFC" indicates hydrogen, chlorine, fluorine, and carbon. "HFC" indicates hydrogen, fluorine, and carbon. "HCC" indicated hydrogen, chlorine, and carbon. In present usage, the term CFC means a fully halogenated compound. In the past, however, the term CFC sometimes was used to refer to the entire family of halocarbon compounds, including those that contained hydrogen. A prefix of "E" is an unofficial designation for a fluorinated ether. In common usage, composition designating prefixes vary by language, for example, HCFC-22 is FCKW-22 in German.

2.3 Possibilities for alternatives

2.3.1 Pure fluids

A number of research centres have undertaken screenings of many possible candidates based on limited property data or the methods mentioned above in Section 2.2.2.4. While these efforts and the development of more reliable screening techniques should be ongoing, a number of fluids can be identified as the most likely alternative refrigerants.

2.3.1.1 Halocarbons

Halocarbons are the focus of intense development efforts by industry. In particular, most of the effort has focused on the one- and two-carbon HFCs and HCFCs. Fluorinated propane (three-carbon) derivatives are also of interest.

2.3.1.2 "Natural refrigerants"

"Natural refrigerants" have seen increased use in recent years. This group includes ammonia, water, carbon dioxide, and the simple hydrocarbons, such as ethane, propane, butane, and isobutane. The term "natural" denotes a fluid which occurs naturally in the environment. Water is, of course, ubiquitous in the environment. Ammonia and carbon dioxide are produced by biological processes; any refrigeration use of these fluids would involve quantities trivial in comparison to natural production. Ethane, propane, butane, and isobutane are found in natural gas. While the global environmental impacts of releasing these fluids in the quantities which might be used in refrigeration applications would be minimal, they are not necessarily benign on a highly local level (hydrocarbons are considered VOCs). Ammonia is an excellent refrigerant but is toxic and flammable. The hydrocarbons have good thermodynamic and transport properties but are highly flammable.

2.3.1.3 Other fluids

Other fluids also show some promise. Fluorinated ethers are being investigated, particularly for specialised applications for which no obvious halocarbon alternative exists. The iodo- (iodine containing) compounds have been proposed as possible alternatives. CF_3I, for example, is claimed to be non-flammable and nontoxic with an atmospheric lifetime of only a few days /Nim94/. However, recent and, as yet unpublished, tests conducted by a reputable toxicity testing laboratory indicate that CF_3I is a cardiac sensitiser at low levels compared to other halocarbon refrigerants; CF_3I also gave positive results in several genotoxicity assays, indicating that it is a possible mutagen. There are also serious concerns regarding the stability of both the fluorinated ethers and iodo-compounds in refrigeration systems.

2.3.2 Mixtures

Refrigerant mixtures represent additional possibilities for replacement working fluids. Mixtures can also allow the use of a refrigerant that would not be acceptable as a pure fluid. The most obvious example is the combination of flammable and nonflammable components to yield a nonflammable mixture. The availability of mixtures is dependent both on the availability of the constituent components and also the development of methods to handle mixtures in the charging and servicing of systems. A number of mixtures are being produced in commercial quantities, particularly as HCFC-22 and R-502 replacements and to service systems designed for CFC-12. Mixtures can be categorised into three types.

2.3.2.1 Azeotropes

Azeotropes exist for particular compositions of some mixtures. Azeotropes exhibit a maxima or minima in the dew and bubble curves. Like pure compounds, they boil and condense at a constant temperature and have identical liquid and vapour compositions. The azeotropic composition, however, varies (sometimes widely) with temperature and pressure.

2.3.2.2 Zeotropic mixtures

Zeotropic mixtures (also called nonazeotropic mixtures and abbreviated NARM for nonazeotropic refrigerant mixture) have compositions of coexisting liquid and vapour which differ. Condensation and evaporation processes occur over a range of temperature in contrast to the isothermal phase change seen with pure components or azeotropes. This range of condensation or evaporation temperature is referred to as "temperature glide." These effects can be exploited to enhance performance, but generally require equipment modifications.

2.3.2.3 Near-azeotropes

Near-azeotropes exhibit such small deviations from azeotropic behaviour to be usable in traditional refrigeration equipment without modification. Near-azeotropes offer the potential to tailor the properties of the working fluid to a particular application, possibly to the point of obtaining a "drop-in" substitute for use in existing equipment. Some so-called azeotropes are, in fact, near azeotropes over much of the typical operating range.

2.3.3 Characteristics of Alternatives

2.3.3.1 Physical properties

A list of candidate pure fluids and mixtures is given in Table 2.2. The fluids are separated into groups according to their commercial availability. The mixtures listed are those that have been commercialised or that are the subject of active industrial research; many other mixtures are possible. This table lists the fluid name or halocarbon number and chemical formula along with four of the most fundamental thermophysical properties per molecular mass (MW), normal boiling point temperature (NBP), critical temperature (T_c), and critical pressure (P_c). For comparison, the fully halogenated compounds are also listed. Most of the data in Table 2.2 have been compiled from the ARTI Refrigerant Database /Cal94b/.

2.3.3.2 Safety data

Chronic toxicity is characterised in terms of Threshold Limit Values (TLVs) which "represent conditions under which it is believed that nearly all workers can be repeatedly exposed day after day without adverse health effects" /ACG92/. For volatile substances, such as refrigerants, TLVs are expressed as parts per million volume concentrations in air. The term TLV is a trademark of the American Conference of Governmental Industrial Hygienists (ACGIH) and properly refers only to exposure limits fixed by that group. Several manufacturers have evaluated similar indices in the absence of ACGIH values; these are noted with an asterisk in Table 2.2. Acute toxicity is also a concern, see, for example /Cal94a/.

Flammability is characterised in terms of two parameters. The lower flammable limit (LFL) is defined by ASTM Standard E 681-85 as "the minimum concentration of a combustible substance that is capable of propagating a flame through a homogeneous mixture of the combustible and a gaseous oxidiser under the specified conditions of test" /AST85/; the pressure. (ASHRAE Standard 34 specifies a different ignition source for the halocarbons, but otherwise adopts the ASTM method.) Heat of combustion is also listed; this parameter can be computed even for nonflammable fluids and is useful for estimating whether a mixture of flammable and nonflammable constituents will sustain and propagate a flame.

The ASHRAE Standard 34 /ASH92b/ safety classifications address both chronic toxicity and flammability. The toxicity classifications are "A" (lower toxicity) and "B" (higher toxicity). Flammability is classified as "1" (no flame propagation), "2" (lower flammability), or "3" (higher flammability). The letters and numbers are combined into a 2x3 matrix , from A1 to B3. The resulting safety classification, designated by a letter and number, is tabulated in Table 2.2 where established. For mixtures, two classifications are assigned: the first represents the classification of the mixture at the "as formulated" composition, and the second is the "classification of the blend composition at the worst case of fractionation."

Table 2.2 ***Summary of possible alternative refrigerants***

Refrigerant		physical data				safety data					environmental data		
number/name	formula/[synonyms]	MW	NBP^5 (_C)	T_c (_C)	P_c (MPa)	TLV (ppm)	LFL^1 (%)	Δh_{comb}^{2} (MJ/kg)	safety^3 group		at. life (years)	ODP	GWP 100 yr
COMMERCIALLY AVAILABLE FLUIDS HFCs, HFC BLENDS, AND OTHER ZERO ODP FLUIDS													
FC-14	CF_4 [carbon tetrafluoride]	88.00	-127.9	-45.7	3.75		none		A1		50,000	0.000	6300**
HFC-23	CHF_3	70.01	-82.1	24.3	4.87	1000*	none	-12.5	A1		250	0.000	12100**
FC-116	CF_3CF_3 [perfluoroethane]	138.01	-78.4	19.9	3.04		none		A1		10,000	0.000	12500**
R-7146	SF_6 [sulfur hexafluoride]	146.05	-63.8	45.6	3.76	1000	none				3200	0.000	24900**
HFC-32	CH_2F_2	52.02	-51.7	78.2	5.80	1000	14.0	9.4	A2		6	0.000	580**
HFC-125	CHF_2CF_3	120.02	-48.1	66.3	3.63	1000*	none	-1.5	A1^p		36	0.000	3200**
HFC-143a	CH_3CF_3	84.04	-47.4	73.6	3.83	1000	7.4	10.3	A2^r		55	0.000	4400**
R-507^r	R-125/143a (50/50) [AZ-50]	98.90	-46.7	70.9	3.79		none		A1			0.000	
R-508	R-23/116 (39/61) [Klea53]	100	-10	-95.7	23.1		none		A1				
R-404A	R-125/143a/134a (44/52/4) [HP62 and FX-70]§	97.60	-46.5	72.1	3.73	1000	none		A1/A1^p			0.000	
R-407A^r	R-32/125/134a(20/40/40)[Klea60]§	90.10	-45.5	82.6	4.54	1000	none		A1/A1^r			0.000	
R-407B^r	R-32/125/134a(10/70/20)[Klea61]§	102.94	-47.3	76.0		1000	none		A1/A1^r			0.000	
R-407C	R-32/125/134a(23/25/52) [Klea66]§ [Suva9000]§	86.2	-43.6	86.1	4.62	1000	none					0.000	
R-410A	R-32/125 (50/50) [AZ-20]	72.56	-50.5	72.5	4.96	1000	none					0.000	
FC-218	$CF_3CF_2CF_3$	188.02	-36.7	71.9	2.68		none		A1		>100	0.000	>34000
HFC-134a	CH_2FCF_3	102.03	-26.1	101.1	4.06	1000*	none	4.2	A1		14	0.000	1300**
E170_	CH_3OCH_3 [dimethyl ether]	46.07	-24.8	128.8	5.32		3.4					0.000	
HFC-152a	CH_3CHF_2	66.05	-24.0	113.3	4.52	1000*	4.8	17.4	A2		1.5	0.000	150**
HFC-227ea	CF_3CHFCF_3	170.03	-18.3	103.5	2.95	1000*	none	3.3			41	0.000	3300**
COMMERCIALLY AVAILABLE NON HALOGENATED REFRIGERANTS ("NATURAL REFRIGERANTS")													
HC-170	CH_3CH_3 [ethane]	30.07	-88.8	32.2	4.89	s.a.^{4}	3.3	57.9	A3			0.000	3
R-744	CO_2 [carbon dioxide]	44.01	-78.4	31.1	7.37	5000	none	0	A1		50-200	0.000	1
HC-290	$CH_3CH_2CH_3$ [propane]	44.10	-42.1	96.8	4.25	s.a.^{4}	2.1	50.3	A3			0.000	3
R-717	NH_3 [ammonia]	17.03	-33.3	133.0	11.42	25	15	225	B2		<1	0.000	neglig
HC-600a	$CH(CH_3)_3$ [isobutane]	58.13	-11.7	135.0	3.65		1.7	49.4	A3			0.000	3
R-764	SO_2 [sulfur dioxide]	64.07	-10.0	157.5	7.88	2			B1			0.000	
HC-600	$CH_3CH_2CH_2CH_3$ [butane]	58.13	-0.4	152.0	3.80	800	1.5	49.5	A3			0.000	3
R-718	H_2O [water]	18.02	100.0	374.2	22.10	none			A1			0.000	0

Table 2.2 ***Summary of Possible Alternative Refrigerants (continued)***

Refrigerant		physical data					safety data			environmental data		
number/name	formula/synonyms§	MW	NBP^5 (_C)	T_c (_C)	P_c (MPa)	TLV (ppm)	LFL^1 (%)	Δh_{comb}^{2} (MJ/kg)	safety^3 group	at. life (years)	ODP	GWP 100 yr
COMMERCIALLY AVAILABLE FLUIDS HCFCs AND HCFC-CONTAINING BLENDS												
R-402A	R-125/290/22 (60/2/38) [HP80]§	101.55	-49.2	75.5	4.13	1000*	none		A1/A1^p		0.021	
R-402B	R-125/290/22 (38/2/60) [HP81]§	94.71	-47.4	82.6	4.45	1000*	none		A1/A1^p		0.033	
R-403A	R-290/22/218 (5/75/20) [69-S]§	91.06	-50.0	93.3	5.08		none		A1/A1^r		0.041	
R-403B	R-290/22/218 (5/56/39) [69-L]§	102.06	-49.5	90.0	5.09		none		A1/A1^r		0.030	
R-408A	R-125/143a/22 (7/46/47) [FX10]§	87.02	-43.5	83.5	4.34	1000*	none				0.026	
HCFC-22	$CHClF_2$	86.47	-40.8	96.2	4.99	1000	none	2.2	A1	13.3	0.055	1700**
–	R-22/124/142b (65/25/10) [FX57]§	96.70	-35.2	105.0	4.70		none				0.048	
R-401A	R-22/152a/124 (53/13/34) [MP39]§	94.44	-33.1	108.0	4.60		none		A1/A1^p		0.037	
R-401B	R-22/152a/124 (61/11/28) [MP66]§	92.84	-34.7	106.1	4.68		none		A1/A1^p		0.040	
R-401C	R-22/152a/124 (33/15/52) [MP52]§	101.04	-28.4	112.7	4.37		none		A1/A1^p		0.030	
R-405A^r	R-22/152a/142b/C318 (45/7/5.5/42.5) [G2015]§	116.00	-27.3	106.1	4.26		none		A1/A1^r		0.028	
R-406A^r	R-22/600a/142b (55/4/41) [GHG]§	89.85	-30.0	123.0	9.7				A1/A2^r		0.057	
R-409A	R-22/124/142b (60/25/15) [FX56]§	97.45	-34.2	107.0	4.50		none		A1/A1^r		0.048	
HCFC-124	$CHClFCF_3$	136.48	-12.0	122.5	3.64	500*	none	0.9	A1^p	5.9	0.022	480**
HCFC-142b	CH_3CClF_2	100.50	-9.8	137.2	4.12	1000*	9.0	9.8	A2	19.5	0.065	2000**
HCFC-123	$CHCl_2CF_3$	152.93	27.9	183.7	3.67	10*	none	2.1	B1	1.4	0.020	93**
HCFC-141b	CH_3CCl_2F	116.95	32.2	204.4	4.25	500*	7.4	8.6		9.4	0.110	630**
HCC-30	CH_2Cl_2 [methylene chloride]	84.93	40.2	237.0	6.08	50	14.6		B2	0.41		9**
FLUIDS LIKELY TO BE AVAILABLE WITHIN 3 - 5 YEARS												
–	R-32/125/143a/134a (10/33/36/21) [HX4]§	94.50	-49.4	77.5	4.01		none				0.000	
–	R-32/125/143a (10/45/45) [FX40]§	90.70	-48.4	72.0	4.05		none				0.000	
–	R-22/152a/124 (40/17/43) [MP33]§	96.62	-28.8				none				0.030	

Table 2.2 *Summary of Possible Alternative Refrigerants (continued)*

Refrigerant		physical data				safety data				environmental data		
number/name	formula/synonyms	MW	NBP (_C)	T_c (_C)	P_c (MPa)	TLV (ppm)	LFL[1] (%)	Δh_{comb}[2] (MJ/kg)	safety[3] group	at. life (years)	ODP	GWP 100 yr
DEVELOPMENTAL CANDIDATES COMMERCIAL AVAILABILITY > 5 YEARS, OR UNCERTAIN												
E125_	CHF_2OCF_3	136.02	-41.9	80.4	3.33					21	0.000	
HFC-41	CH_3F	34.03	-78.4	44.3	5.88					4	0.000	340
HFC-161	CH_3CH_2F	48.06	-37.1	102.2	4.70		3.8			<1	0.000	
E143a_	CH_3OCF_3	100.04	-24.1	104.9	3.59					4.1	0.000	360
HFC-134	CHF_2CHF_2	102.03	-23.0	118.7	4.62	none		4.3		11.9	0.000	1200**
FC-13I1	CF_3I	195.91	-22.5	121.9	4.04	none						
HFC-245cb	CH_3CF2CF_3	134.05	-18.3	108.5	3.26					1.8	0.000	
HFC-227ca	$CHF_2CF_2CF_3$	170.03	-17.0	106.3	2.87					15	0.000	
RC-318	cyclo-$CF_2CF_2CF_2CF_2$-	200.04	-5.8	115.4	2.78	none			A1		0.000	
HFC-236cb	$CH_2FCF_2CF_3$	152.04	-1.4	130.2	3.12					3.2	0.000	
HFC-236fa	$CF_3CH_2CF_3$	152.04	-1.1	130.7	3.18					250	0.000	8000**
HFC-254cb	$CH_3CF_2CHF_2$	116.06	-0.8	146.2	3.75					1.6	0.000	
HFC-236ca	$CHF_2CF_2CHF_2$	152.04	5.1	155.2	3.41						0.000	
E134_	CHF_2OCHF_2	118.03	6.2	153.5	4.23		3.3			2.8	0.000	
HFC-236ea	CHF_2CHFCF_3	152.04	6.6	141.2	3.53			5.4		1.2	0.000	
HCC-160	CH_3CH_2Cl	64.51	12.4	186.6	5.24		3.6	20.6		<1	0.000	
HFC-245fa	$CHF_2CH_2CF_3$	134.05	15.3	157.6	3.64		8.9	7.9		8.6	0.000	
HFC-245ca	$CH_2FCF_2CHF_2$	134.05	25.5	178.5	3.86	none		8.4		7	0.000	610**
HCFC-123a	$CHClFCClF_2$	152.93	28.0	188.5	4.47	none						
E245fa1	$CHF_2OCH2CF_3$	150.05	29.2	170.9	3.73					5.8	0.000	
E245cb1	$CHF_2OCH_2CF_3$	150.05	34.0	185.2							0.000	

Table 2.2 ***Summary of Possible Alternative Refrigerants (continued)***

Refrigerant number/name	formula/synonyms	physical data MW	NBP (_C)	T_c (_C)	P_c (MPa)	safety data TLV (ppm)	LFL[1] (%)	Δh_{comb}[2] (MJ/kg)	safety[3] group	environmental data at. life (years)	ODP	GWP 100 yr
CFCs AND HALONS (FOR COMPARISON)												
R-503	R-23/13 (40.1/59.9)	87.28	-87.8	19.5	4.36	1000*	none				0.599	
CFC-13	$CClF_3$	104.46	-81.4	28.8	3.87	1000*	none	-3.0	A1	640	1.000	11700**
BFC-13B1	$CBrF_3$ [Halon 1301]	148.91	-57.8	-67.0	3.96	1000	none		A1	65	16.000	5600**
R-502	R-22/115 (48.8/51.2)	111.64	-45.4	82.2	4.08	1000	none		A1		0.283	
CFC-115	$CClF_2CF_3$	154.47	-39.1	79.9	3.15	1000	none	-2.1	A1	1700	0.600	9300**
R-500	R-12/152a (73.8/26.2)	99.31	-33.5	105.5	4.42	1000*	none		A1		0.738	
CFC-12	CCl_2F_2	120.91	-29.8	112.0	4.11	1000	none	-0.8	A1	102	1.000	8500**
CFC-114	$CClF_2CClF_2$	170.92	3.8	145.7	3.25	1000	none	-3.1	A1	300	1.000	9300**
CFC-11	CCl_3F	137.37	23.8	198.0	4.41	1000	none	0.9	A1	50	1.000	4000**
CFC-113	$CClF_2CCl_2F$	187.38	47.6	214.1	3.44	1000	none	0.1	A1	85	0.800	5000**

NOTES FOR TABLE 2.2:

[1] lower flammability limits are expressed as volume % in ambient air

[2] heat of combustion calculated assuming complete reaction to most stable products in vapor state: CO_2, HF (or F_2 if insufficient H), Cl_2, N_2, and H_2O (if excess H); negative and small positive values indicate that reaction with oxygen is not energetically favorable

[3] safety group classification assigned by ASHRAE Standard 34-1992

[4] classified as a simple asphyxiant by the ACGIH. Such compounds "act primarily as simple asphyxiants without other significant physiologic effects." Other compounds listed here present an asphyxiation hazard, but are assigned TLV values at levels below those causing asphyxiation.

[5] for blends, the bubble point temperature is tabulated

[p] provisional safety classification (pending additional test data)

[r] recommended designation and safety classification; not yet approved for ASHRAE Standard 34 (subject to public review and final approval)

*TLV not established by ACGIH, estimate of comparable index based on limited or incomplete toxicity testing

_E designation is an unofficial extension of the ASHRAE numbering standard

[§] some refrigerant synonyms are manufacturer's trade names

_no ASHRAE Standard 34 designation has been assigned to this fluid or mixture

** newest lifetime and GWP values have been taken from UNEP/ WMO Scientific Assessment 1994/95

2.3.3.3 Environmental properties

The environmental impacts of the fluids in Table 2.2 are characterised by their ozone depletion potential (ODP), relative to CFC-11, their global warming potential (GWP), relative to carbon dioxide, and their atmospheric lifetime. The atmospheric lifetime is defined as the time after which the concentration of an emitted chemical has decreased by *1/e* (approximately 64 %).
The ODP and atmospheric lifetime values are from WMO Report No. 20 /WMO89/; the GWP values are from the report /IPC92/ of the Intergovernmental Panel on Climate Change (IPCC) and as far as updates are available, from the 1994/95 UNEP/WMO Scientific Assessment. These values are continually being re-evaluated as additional data become available. For refrigeration applications, the GWP of any refrigerant that may be emitted during operation, servicing, or disposal is best considered in conjunction with the indirect global warming impact resulting from the production of the energy needed to power the system; it is not practical, however, to list such a total equivalent warming impact (TEWI) in a brief summary table. TEWI values may be found in the AFEAS report /Fis91/; see also /Cal93a/ and /Cal93b/. It cannot be ruled out that additional environmental properties may be important in the future.

2.3.3.4 Availability

The availability of test samples (up to a few tonnes) and production quantities (thousands of tonnes) of the possible alternatives is significant in assessing a candidate fluid as a viable alternative to the CFCs, at least in the near term. The availability of equipment designed for a new fluid must also be considered. The availability is indicated in Table 2.2 by three general categories. The fluids listed as "commercially available" represent the best possibilities for meeting the CFC phaseout targets of the Montreal Protocol (these fluids are commercially produced but some of them may not be available from traditional refrigerant suppliers). The fluids listed as "fluids likely to be available within 3 - 5 years" are under active test and development and are mostly intended to be HCFC replacements; test samples of these fluids are available now. For the fluids listed as "developmental," development is many years behind the others, and the eventual availability of production quantities is uncertain. The fluids in this group should be explored; other crucial goals must not, however, await any new "miracle" refrigerant.

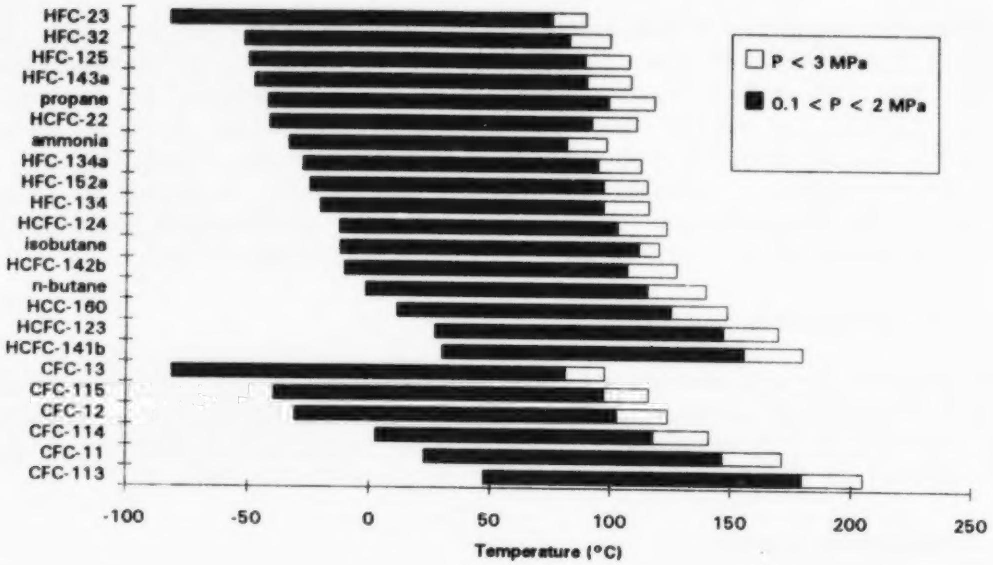
2.3.3.5 Applicable temperature range

The range of evaporating and condensing temperature over which a refrigerant is typically used is determined primarily by vapour pressures. Operation of the evaporator below the normal boiling point (the temperature at which the vapour pressure is equal to one standard atmosphere, 0.101 MPa) is normally avoided. (The major exception is low pressure centrifugal compressors.) The absolute upper limit for the condensation temperature is the critical temperature, but a more practical upper limit is the temperature at which the vapour pressure is 2 or 3 MPa. These limits are depicted in Figure 2.1. The decomposition temperature of a fluid must also be considered.

2.3.4 Tradeoffs

Table 2.2 reveals that no fluid is perfect in all regards (all of the fluids listed have one or more drawbacks: toxicity; moderate to high flammability; low, but non zero, ODP; and/or moderate GWP and atmospheric life). The acceptability of a given fluid will depend on the application. Certain commercial and industrial applications can, with appropriate safety measures, accommodate a toxic or flammable refrigerant.

Figure 2.1 ***Practical range of evaporating and condensing temperatures for some alternative refrigerants and CFCs. (Figure adapted from /Vam90/.)***



However, this might not be acceptable in a residential application. On the other hand, the low charge of some home refrigerators greatly reduce the hazards associated with a flammable refrigerant. However, for systems with a larger charge (e.g. heat pumps using direct expansion coils) these hazards cannot be overlooked.

The consideration of the global warming impact of a refrigerant is best approached by the TEWI (total equivalent warming impact) concept, which takes into account the energy consumption of the system as well as the GWP resulting from emissions of the refrigerant over the life of the equipment. Using this approach, refrigerants with a relatively high GWP that would not be acceptable in leak-prone applications, such as automotive air-conditioning, might be acceptable, and perhaps even have the lowest TEWI, in applications that tend not to leak (e.g. domestic refrigerators). Ultimately, the choice of refrigerant is a compromise to best balance technical and economic parameters in view of the political considerations that will dictate the relative weight given to safety, environmental, and energy efficiency factors.

2.4 Thermophysical properties in the vapour compression cycle

2.4.1 Thermodynamic properties

Thermodynamic properties determine the efficiency and capacity of the vapour compression cycle and thus are key data needed for designing refrigeration equipment and for comparing one refrigerant with another. Of prime importance is the energy involved in the various processes, thus the need for accurate enthalpy values. The ideal compression process is at constant entropy; real compressors are often compared to the isentropic process. Also important are the operating pressures of the condenser and evaporator; these are largely a function of the vapour pressure. For positive displacement (e.g. piston) compressors, the density of the vapour largely determines the mass flow rate through the compressor and thus the refrigeration capacity. For centrifugal compressors, the maximum speed of the impeller is limited by the vapour sonic velocity; the relative pressure rise developed by the compressor is a function of the impeller speed and the inverse of the square root of the refrigerant molecular weight.

Thermodynamic properties are invariably formulated in terms of an equation of state. An equation of state not only correlates directly measured quantities in a thermodynamically consistent way, but also allows the evaluation of derived quantities. For example, enthalpy, entropy, and specific heat are obtained by calculations involving up to second-order derivatives of a pressure-volume-temperature equation of state. Accuracy's of one percent would be adequate for pressures and densities in themselves; their importance to the derived quantities, however, places much more stringent requirements on the required accuracy of the p-V-T data (one-tenth of one percent or better).

2.4.1.1 Mixture thermodynamic properties

Mixture properties are also formulated in terms of an equation of state. This can take the form of a mixture equation based on the properties of the constituent pure components and, perhaps, also a "mixing parameter" to describe the departure from ideal mixing. An equation of state can also be formulated for a specific mixture composition.

2.4.2 Transport properties

While the thermodynamic properties of a fluid determine its performance in the vapour compression cycle, the transport properties have a major impact on the design of refrigeration equipment. Thus the transport properties have a major influence on how closely we can economically approach the theoretical efficiency of the thermodynamic cycle.

Transport properties are particularly important in the design of the heat exchangers (condenser and evaporator). The effectiveness of heat transfer with the refrigerant is expressed in terms of a heat transfer coefficient. For the final optimisation of heat exchanger design these heat transfer coefficients are often experimentally determined for the exact combination of refrigerant and surface used. In the screening and preliminary design stages, heat transfer coefficients are estimated via correlation's involving thermal conductivity, viscosity, surface tension, density, and heat capacity.

2.5 Data status

The data required for a fluid increase as it progresses from a possible candidate to full commercial production and use. A few basic parameters (such as normal boiling point) can be used to screen among many possible candidates to select a more limited set on which to focus development efforts. At the other extreme, extensive, high-accuracy data of many types are required for a fluid in widespread use. The data available for the various candidate refrigerants identified above will be assessed.

2.5.1 Pure fluids thermophysical properties

For the thermodynamic and transport properties, the level of data can be classified into the following categories:

(1) screening parameters, e.g. normal boiling point temperature, critical point parameters, molecular structure, and perhaps thermal conductivity and viscosity at some reference condition

(2) primary data, e.g. saturated liquid density, vapour pressure, and ideal gas heat capacity over a range of temperature, and thermal conductivity and viscosity along the saturation boundary, also over a range of temperature

(3) comprehensive data, including, for example, viscosity, thermal conductivity, and pressure-volume-temperature data in the vapour and compressed liquid regions, more extensive saturation properties, and confirming data, such as heat capacity and sound speed data

(4) standard reference data an extensive collection of high quality data covering wide ranges of temperature and pressure

2.5.1.1 Screening parameters

The screening parameters are needed to sort among the hundreds of fluids which might be considered for use. Almost by definition, these data must be available to even consider a fluid. Fortunately, information such as the normal boiling point is available for a huge number of fluids, including all of the fluids listed in Table 2.2.

2.5.1.2 Primary data

The next level of data, the primary data, represent the minimum information required to generate reliable estimates of the thermophysical properties. With such information, the performance of a fluid in the vapour compression cycle can be estimated. The transport properties are somewhat lower in priority than the thermodynamic properties and initial studies often do not consider the transport properties, implicitly assuming that fluids with similar thermodynamic properties will have comparable transport properties.

2.5.1.3 Comprehensive data

The comprehensive data are the minimum set which allows a traditional formulation of the properties using an equation of state. Comprehensive thermodynamic properties have been measured for most of the CFC refrigerants in use today, most of the "new" HFCs and HCFCs, as well as ammonia and the simple hydrocarbons. The transport properties for the many of the fluids fall short of this level, however.

2.5.1.4 Standard reference data

The final category, that of standard reference data, includes essentially the same types of data as the comprehensive category, but the data would extend over a wider range of temperature and pressure, be more closely spaced, especially near the critical point, and should also be of the highest obtainable accuracy. This level of data is not ordinarily justified for equipment design purposes, but is required for the purposes of model development and for defining a reference fluid for use in extended corresponding states models.

2.5.1.5 Status of thermophysical property data

The status of the various candidate fluids is given in Table 2.3 according to the above classification scheme. One can infer from this table the areas where more information is needed. As a minimum, primary data should be gathered for all of the fluids which are promising alternatives. Comprehensive data is the desired level for all fluids being actively developed or seriously evaluated in machinery. The data necessary to develop a material to reference fluid quality restricts this category to a very limited number of fluids. Such a fluid should be well chosen. A fluid in very widespread use would deserve such status. A fluid might also be chosen for more theoretical reasons to serve as a reference fluid for the development of equations of state or other property models which could then be used to extend the more limited information available for other fluids. Extensive data for HFC-134a and HFC-152a are now becoming available and should soon be at the reference fluid level. At least one of the other new refrigerants should also be developed to this level.

2.5.2 Mixtures

Mixture data are needed to allow an assessment of mixtures as CFC and HCFC replacements and to aid in the identification of possible azeotropic mixtures. A wide variety of measurements on refrigerant mixtures have been reported in the literature. Unfortunately, most of the mixtures studied contain at least one component which is fully halogenated; only recently have limited data become available for mixtures of hydrogen-containing halocarbons.

A variety of information can be used in extending mixture models. The most basic and useful data are bubble point pressures over a range of temperature and composition. Liquid density and coexisting liquid and vapour compositions are also desirable. The transport properties for refrigerant mixtures are especially important since there is some evidence that there may be substantial degradation of desirable properties due to non-ideal mixture effects, leading to heat transfer penalties. As with the pure fluids, establishing an extensive data set for one or more reference mixtures would be highly useful in developing and verifying mixture models; work along these lines is now in progress. Exhaustive measurements such as pressure-volume-temperature data for the single-phase region would be justified for a mixture that has a high probability of being commercialised.

Table 2.3—Data status of possible alternative refrigerants

Fluid		thermophysical properties						lubricant[1]		materials	toxicity	
		primary		comprehensive		ref. data				compat.	short	long
number/name	formula/synonym	thermo.	trans.	thermo.	trans.	thermo.	trans.	ident.	avail		term	term
COMMERCIALLY AVAILABLE FLUIDS_HFCs AND OTHER ZERO ODP FLUIDS												
FC-14	CF_4 [carbon tetrafluoride]	1	1	-								
HFC-23	CHF_3	1	1	1	-	-		1	1		1	-
FC-116	CF_3CF_3 [perfluoroethane]	1	1	-	-			-			1	
SF_6	SF_6 [sulfur hexafluoride]	1	1	1	1	-					1	-
HFC-32	CH_2F_2	1	1	1	1	1	1	-	-	-	1	*
HFC-125	CHF_2CF_3	1	1	1	1	1	1	-	-	-	1	*
HFC-143a	CH_3CF_3	1	1	1	1	1	1	-	-	-	1	-
FC-218	$CF_3CF_2CF_3$	1									1	
HFC-134a	CH_2FCF_3	1	1	1	1	1	1	1	1	1	1	
E170	CH_3OCH_3 [dimethyl ether]	-	-							-	1	
HFC-152a	CH_3CHF_2	1	1	1	1	1				1	1	1
HFC-227ea	CF_3CHFCF_3	1	1	1	-			1	1	1	1	1
COMMERCIALLY AVAILABLE FLUIDS_"NATURAL REFRIGERANTS"												
HC-170	CH_3CH_3 [ethane]	1	1	1	1					1	1	1
R-744	CO_2 [carbon dioxide]	1	1	1	1	1		1	1	1	1	1
HC-290	$CH_3CH_2CH_3$ [propane]	1	1	1	1	1	1	1	1	1	1	1
R-717	NH_3 [ammonia]	1	1	1	1	1	-	1	1	1	1	1
HC-600a	$CH(CH_3)_3$ [isobutane]	1	1	1	-	-		1	1	1	1	1
R-764	SO_2 [sulfur dioxide]	1	1					1	1	-	1	-
HC-600	$CH_3CH_2CH_2CH_3$ [butane]	1	1	1	-	-		1	1	1	1	1
R-718	H_2O [water]	1	1	1	1	1	1	1	1	1	1	1
COMMERCIALLY AVAILABLE FLUIDS_HCFCs												
HCFC-22	$CHClF_2$	1	1	1	1	1		1	1	1	1	1
HCFC-124	$CHClFCF_3$	1	1	1	-			1	1		1	*
HCFC-142b	CH_3CClF_2	1	1	-				1	1	1	1	1
HCFC-123	$CHCl_2CF_3$	1	1	1	1	1		1	1	1	1	1
HCFC-141b	CH_3CCl_2F	1	1	-				1	1	-	1	1
CHC-30	CH_2Cl_2 [methylene chloride]	-	-					1	1	1	-	-

Table 2.3—Data Status of Possible Alternative Refrigerants

Fluid		thermophysical properties						lubricant[1]		materials	toxicity	
		primary		comprehensive		ref. data				compat.	short	long
number/name	formula/synonym	thermo.	trans.	thermo.	trans.	thermo.	trans.	ident.	avail		term	term
DEVELOPMENTAL CANDIDATES COMMERCIAL AVAILABILITY > 5 YEARS, OR UNCERTAIN												
E125_	CHF_2OCF_3	ı										
HFC-161	CH_3CH_2F	~										
E143a_	CH_3OCF_3	ı										
HFC-134	CHF_2CHF_2	ı									ı	
CF_3I	CF_3I											
HFC-245cb	CH_3CF2CF_3	~										
HFC-227ca	$CHF_2CF_2CF_3$	~										
RC-318	cyclo-$CF_2CF_2CF_2CF_2$	~										
HFC-236cb	$CH_2FCF_2CF_3$	~										
HFC-236fa	$CF_3CH_2CF_3$	~										
HFC-254cb	$CH_3CF_2CHF_2$	~										
HFC-236ca	$CHF_2CF_2CHF_2$	~										
E134	CHF_2OCHF_2	ı	~									
HFC-236ea	CHF_2CHFCF_3	ı										
HCC-160	CH_2ClCH_3	ı	ı	~	~			ı	ı	ı	ı	ı
HFC-245fa	$CHF_2CH_2CF_3$	~										
HFC-245ca	$CH_2FCF_2CHF_2$	~										
HCFC-123a	$CHClFCClF_2$	~									ı	
E245fa_	$CHF_2OCH2CF_3$	~	~									
E245cb_	$CHF_2CF_2OCF_3$	~	~									

NOTES FOR TABLE 2.3:

see text for explanation of "primary," "comprehensive," and "reference data"

ı indicates data available or testing complete

~ indicates data of limited range and/or data for only some properties and/or testing in progress

* indicates PAFT testing in progress

a blank indicates no data

_E designation is an unofficial extension of the ASHRAE numbering standard

[1] a ı indicates that a suitable lubricating oil is available (avail.) or has been identified (ident.) in laboratory tests

Table 2.4 ***Data required for the various stages in the commercialisation of a new refrigerant***

	area of research				
stage	fluid development	thermophysical properties	materials compatibility	health/safety/ environmental	equipment testing and design
screening	bench-scale synthesis (gram quantities)	screening parameters (NBP, etc.)		estimates based on experience with similar compounds	
qualification of leading candidates	preliminary process design, synthesis of kg quantities	primary data	materials tests, identify/develop lubricant	flammability, short-term toxicity, ODP, GWP, etc.	tests in unmodified equipment
design for chosen refrigerant	pilot-plant production of tonne quantities	equation of state, comprehensive data	continued materials and lubricant tests and development	long-term toxicity, hazard analysis, fate in environment	design & test of prototypes, field trials
first commercial products					
refinement and optimisation	process refinement leading to cheaper product	reference fluid quality data	monitor long-term reliability in actual use	analysis of accidents/failures	continued optimisation of equipment design

2.5.3 Priorities for the thermophysical properties

While there has been considerable progress made in the measurement of high priority data identified in the last UNEP review process, the need to also phaseout the HCFCs has increased the number of pure fluids and mixtures needing attention. Remaining as high priority items are the following:

> measurements of thermodynamic and transport property data for mixtures of the HFCs and HCFCs;
>
> measurement of the transport properties of the leading candidates;
>
> collection of at least primary data for additional candidate fluids, especially for fluids that may serve as substitutes for the HCFCs, e.g. the fluorinated ethers and fluorinated propanes; and
>
> development of at least one additional fluid to the level of a standard reference refrigerant for use in model development and testing; HCFC-124 and/or HFC-32 are probably the best choices, both because of their likely commercialisation and theoretical considerations: HCFC-124 has an extremely wide two-phase range, and HFC-32 has an extremely large dipole moment to size ratio.

Completion of these tasks would enable the evaluation of a wide variety of candidate fluids and thus allow the best choice of working fluid for the various applications. Based on these results, priorities could then be established for further work to better characterise the refrigerants and/or refrigerant mixtures to be used in new equipment.

2.5.4 Other data

While the thermophysical properties are essential for screening, the determination of cycle efficiency, and equipment design, other properties are as important or more important in the commercialisation of a new refrigerant. Investigations in the areas of thermophysical properties, safety and environmental factors, material compatibility (including lubricant compatibility), and testing in equipment must all proceed in parallel to minimise the time required to bring a new fluid into widespread commercial use. The status of testing for these properties is summarised in Table 2.3. The relationships between the various parallel efforts is outlined in Table 2.4.

2.5.5 Time frame to obtain crucial data

2.5.5.1 Screening of possible alternatives

The basic data such as boiling point and critical parameters are available or can be reasonably estimated for a few thousand compounds. These parameters have yet to be established for some of the "long-shot" compounds whose molecular structure identifies them as possibly useful. This process is essentially complete, although additional pure fluids (e.g. CF_3I) and, especially, mixtures continue to be proposed. However, the uncertainty surrounding the acceptability of the GWP of some of the HFCs and the need to replace the HCFCs has reopened the need to consider additional fluids and mixtures.

2.5.5.2 Thermodynamic and transport properties

The measurement of thermophysical properties for a hitherto unknown substance in the quantity and quality necessary to permit the design of refrigeration equipment is a tedious task. The necessary equipment and expertise do, however, exist in a number of research centres and work is well under way. It is also possible, in the interim, to apply estimation methods in order to extend limited information. Needs in this area will continue for many years, especially if mixtures find widespread use or if additional fluids continue to be developed.

The measurement of thermophysical properties requires only small quantities of fluid sample (on the order of a few hundred grams) so that this should not be a major impediment. Indeed, the determination of these properties may be the most effective use of a material that is in short supply since knowledge of the thermophysical properties may reduce the need for extensive equipment tests requiring many kilograms or even tonnes of refrigerant.

2.5.5.3 Flammability data

Although flammability data are not available for some of the long shot possibilities, the test to determine flammability is straightforward and should not be a rate-limiting factor. Further refinement of the test method is needed to clarify and make more reproducible the results for marginally flammable fluids. There is great uncertainty, however, whether or not flammable refrigerants will be acceptable for many applications.

2.5.5.4 Materials compatibility tests

The identification of a suitable lubricating oil requires often lengthy, "iteration and conversions" experimentation. Included in this process would be tests of the chemical stability of oil-refrigerant mixtures in contact with common materials of construction and possible contaminants such as water. Similar tests would be required to ascertain the suitability of desiccants, insulation's, and seal materials. To estimate the time necessary to identify and confirm the suitability of lubricating oils, seals, materials of construction, etc. is very difficult. The tests are not only inherently time consuming and expensive but there is also no guarantee of success. It may take many trials to find a suitable material. This could be a real show-stopper for an otherwise promising refrigerant. More than 2 - 3 years could easily be required for this development and testing process for a new fluid. An extensive test program conducted by the Air-Conditioning and Refrigeration Technology Institute in the U.S. has yielded extensive data for many of the leading candidates /Ern94/, /Szy94/, /Cal94b/.

2.5.5.5 Toxicity

This is perhaps the most expensive and time consuming step in the qualification of a new refrigerant. Although a preliminary indication of toxicity can be obtained in a few months, the rate-determining step is the long-term testing necessary to reveal any chronic toxicological effects. These tests cannot be speeded up. Long-term testing for HFC-134a, HCFC-123, and HCFC-141b is now essentially complete. Testing for HFC-32, HCFC-124, and HFC-125 will be completed by 1994 or 1995. For the hydrocarbons, CO_2, and ammonia, accepted exposure levels have been established. For many of the hydrocarbons, however, the testing was done many years ago and not using current testing protocols; the data are incomplete, and further testing may be required to fully determine their chronic toxicity (e.g. cyclopentane toxicity testing has been started in Europe recently). In the case of hydrocarbons, these are available in a wide range of purities; the purity of the chemical applied determines the percentage of (mostly aromatic) contaminants, which are important in toxicity testing studies. Toxicity testing must be complete before a new refrigerant can be applied on a large scale in any domestic application. Positive intermediate results for some of the new fluids have, however, allowed a go-ahead for process development, equipment design, etc., although at considerable financial risk.

2.5.5.6 Environmental acceptability data

These data include the atmospheric lifetime, decomposition products, and the impact of a substance on ozone depletion, greenhouse warming, low-level smog formation, and possible effects on ground water (this last factor is primarily a concern for the higher-boiling substances used as solvents). These data are of utmost importance. The values of atmospheric lifetime and GWP/TEWI which will be acceptable in the long term have not been decided; this is a major uncertainty facing system designers. Also needed are reliable values for the GWP and atmospheric lifetime of the possible HCFC substitutes and a greater level of confidence in the environmental indices for all of the alternatives. A final verdict on environmental impact may require many decades.

2.6 Concluding remarks

A fluid must satisfy numerous criteria in order to be acceptable as a refrigerant. Despite problems with the fully halogenated CFCs, the hydrogen-containing halocarbons remain as the most promising candidates for replacement working fluids. Ammonia and the hydrocarbons will also see use in a broader range of applications. There also seems to be no reason to abandon the vapour compression cycle because of environmental problems with one type of working fluid. Future restrictions on the HCFCs raises serious concerns, however. There is at present no clear choice for replacing HCFC-22 nor for replacing HCFC-123, which itself is a replacement for CFC-11. Numerous candidates, focusing on mixtures, are presently being evaluated. Very likely, a variety of fluids and blends will be used to replace the CFCs and HCFCs now in use. It would also be prudent to investigate other fluid types.

Among the criteria required of a refrigerant, the thermophysical properties are of major importance. Thermophysical property data have recently become available to evaluate the leading new refrigerants and to permit equipment design. The most significant remaining needs are for comprehensive data and models for refrigerant mixtures. Such data are vital in order not to lose the opportunity to select the best working fluids for the next generation of refrigeration equipment.

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3 Domestic refrigeration

3.1 Introduction

Domestic refrigerator-freezers, used primarily for food preservation, are an important end user of CFCs. Approximately 62 million new units are manufactured world-wide each year and hundreds of millions are currently in use. It is anticipated that the production of refrigerator-freezers will substantially increase in the near future due to an increased demand, especially in Article 5(1) countries. In order to protect the environment, it is important that the industry incorporates non-CFC refrigeration system designs as early as possible while reducing current levels of energy consumption.

The majority of refrigerator-freezers employ the vapour compression refrigeration cycle with CFC-12 as the working fluid. The excellent characteristics of CFC-12 and its use over the past fifty years has led to highly efficient and reliable compressors and other refrigeration system components. Studies have shown that refrigerator-freezers give satisfactory performance for approximately 15 to 20 years. This high degree of reliability has caused consumers to expect long service life from refrigerator-freezers and other appliances in general. Because of consumer expectations, most manufacturers warrant the compressors for a period of five to seven years and the entire appliance for one year /ASH88/. In this context, a substitute refrigerant-lubricant combination must be chosen with equal reliability as CFC-12. Thus, new testing methods have been created to measure alternate refrigerant characteristics to avoid possible failures in the early design phase and maintain a high degree of reliability for future production units.

The efficient use of energy has recently assumed more importance due to the increasing cost of electricity and increased emphasis on reducing greenhouse gases. Global efforts are being made to develop refrigerator-freezers with higher energy efficiency to aid in lowering the indirect emissions from power plants. For domestic refrigeration operating on substitute refrigerants, the indirect contribution is several times greater than the direct contribution from the refrigerant (for CFC-12, direct emissions are of the order of 20%, assuming no reclamation or recycling). From a global warming perspective, it is paramount to select the most efficient refrigerant irrespective of the refrigerant global warming potential (GWP).

3.2 Energy efficiency

Energy efficient domestic refrigerator-freezers would substantially contribute to world-wide efforts to reduce the energy consumption and global warming. Manufacturers of these appliances along with research institutions are making continuing efforts to reduce energy consumption. Lower energy consumption so far is being attained mainly as a result of high efficiency compressor designs. Improvements in refrigeration systems such as use of high efficiency finned heat exchangers, proper air flows over the heat exchangers and improved gasketting etc. are also contributing significantly to energy reductions in refrigerator-freezers.

For the last few years, efforts are being made all over the world to achieve substantial reduction in energy consumption. The research and development work is being concentrated on the following two aspects along with the above mentioned product design considerations.
1. Improved Insulation;
2. Use of Advanced Vapour Compression Cycle.

3.2.1 Influence of improved insulation

Heat leakage through the insulated cabinet determines a major fraction of the energy required by a refrigerator-freezer. As a result, the thermal efficiency of a refrigerator-freezer is strongly dependent on the effectiveness of the cabinet insulation. Rigid polyurethane foam blown with CFC-11 is the dominant insulation selected for use in typical current production refrigerator-freezers. Many of these applications use the foam as an integral element of the cabinet structure in addition to its use as a thermal insulation. Broadening the foam application requirements in this manner broadens the parameter that must be addressed to when assessing alternatives to current practices. The comments below focus on thermal insulation considerations. Care must be taken, however, to assure that structural considerations are properly addressed and overall performance of the appliance is not degraded. Rigorous product and factory safety criteria must not be compromised. The material flammability behaviour must be properly addressed and the material toxicology must be rigorously demonstrated to be safe.
For extensive information, the report of the UNEP TOC report on foams should be consulted.

3.2.1.1 In-kind technology

CFC-11 blown insulating foam is being rapidly eliminated from refrigerator-freezer production throughout the world. Conversions to decrease the production demand for ozone depleting substances are being achieved almost exclusively through the application of so-called in kind technology employing reduced or alternative blowing agents in reformulated rigid polyurethane foams. Initial applications of reduced CFC-11 blown foams occurred in Western Europe in 1989. A German manufacturer later began the conversion to alternative blowing agents with the application of cyclopentane blowing agent. Differences in national material selection preferences are evident as the conversion to alternative blowing agents in refrigerator-freezer applications progresses. Conversion in the three largest developed nation markets can be summarised as follows:

* Europe is generally converting to cyclopentane formulations with some manufacturers making intermediate conversions to HFC-134a, HCFC-141b or blends of HCFC-142b and HCFC-22. The main motivation for these selections are believed to be wide spread consumer demand for products that do not attack the Ozone layer and pending regulations to minimise primary global warming effects. Intermediate conversions are believed to be motivated by investment timing for facility changes necessary to handle flammable materials or to convert from froth foam processes.
* US manufacturers are predominantly converting to HCFC-141b because of constraints introduced through product energy and VOC factory emission standards. The adequacy of data available for cyclopentane toxicological review also has been questioned.

- Japanese manufacturers are generally converting to HCFC-141b because of product energy constraints with some selected models being produced with cyclopentane.

Any use of an HCFC alternative can only be an interim solution because of the future need to phaseout their use and apply materials that do not deplete the ozone layer. Hydrocarbons such as cyclopentane, are one class long term options. Focused research effort is also being devoted to hydrofluorocarbon (HFC) options to HCFC-141b. HFC-245, HFC-356, and HFC-365 are among several options currently being evaluated (further information to be taken from the Report of the UNEP TOC "Foams", 1994/95 Assessment /UNEP94/).

The principals underlying both current and future selection preferences are the subject of active current debate. The summary of the thermal insulating effectiveness of several alternative blowing agents for rigid polyurethane foam presented in Table 3.1 is believed to present an internally consistent perspective of their relative performance. Please note that blowing agent options are listed in their order of thermal insulating effectiveness.

Table 3.1 Energy performance of blowing agents in foam /UNEP94/

Blowing agent option	k-factor (mW/m-K)	k-factor Index	Energy Consumption (%) increase
Japan or U.S. CFC-11 foam	16-18	100	0
HFC-245ca foam	*	102 **	***
HFC-245eb foam	*	103 **	***
HCFC-141b foam	18-19	103	2.0
Eur. reduced CFC-11 foam	18.5-19.5	112	8.5
HFC-356 foam	*	112	***
Cyclopentane foam	19.5-20.5	118	12.5

* Limited data available; not directly comparable to other options.

** Data from single published source; index calculated using CFC-11 data.

*** No data available.

The thermal insulating effectiveness of the CFC-11 blown foams used by Japanese or U.S. manufacturers and the reduced CFC-11 content foams used by European manufacturers are shown for reference. The different thermal insulating performance of these two historical production options may provide insight to interpret some apparently conflicting claims of relative thermal insulation performance being made for the next generation blowing agents. Carbon dioxide (or water blown systems) and various HCFCs other than HCFC-141b are among the blowing agent options omitted from this summary because they are not broadly considered for application in refrigerator-freezer foams. Carbon dioxide has significantly poorer thermal insulating effectiveness, particularly after ageing. HCFC-141b is favoured versus other HCFCs because of its thermal insulating effectiveness and compatibility with existing high pressure processing equipment. All HCFC options have the disadvantage of being interim solutions because of the future phaseout regulations. HFC-134a is a candidate not included in this table. Limited data for

HFC-134a show comparable thermal insulating effectiveness to cyclopentane. Versus cyclopentane, HFC-134a is disadvantaged with regards to greenhouse warming, but has the advantage of being non-flammable. Similar to many other candidates, its application would require significant factory equipment modifications.

3.2.1.2 Not in-kind technology

Vacuum insulation panels (VIP's) are the leading not-in-kind technology being considered for application in refrigerator-freezers. Pilot production capabilities for two different types of VIP's have been established to support market development initiatives: silica powder filled plastic or composite film envelopes and fiberglas filled welded stainless steel envelopes. Characteristics values for these two options are summarised in Table 3.2. Other filler alternatives, such as open cell polymeric foams, are also being pursued but are in the early stages of investigation.

Table 3.2 Vacuum insulation panel characteristics /Men94/

Filler	Silica Powder	Fiberglas
Envelope	Plastic film	Stainless Steel
k-Factor, mW/m-deg K	6-8 **	2.4 **
Vacuum Level, mm Hg	1.0-10.0	0.001-0.01

** Center panel values; edge losses must be taken into consideration.

Higher vacuum levels provide better thermal insulation, but more diffusion resistant envelopes are required to maintain insulating effectiveness. The metals selected for the more impervious envelopes create skin and edge thermal shunts which significantly affect the average, or effective, VIP performance.

Vacuum insulation panels are supplements to foam insulation in refrigerator-freezers. They are not substitutes for foam insulation, nor do they radically alter the amount or thermal effectiveness of foam required for refrigerator-freezer. They arguably are more properly viewed as energy enhancing assembly components. Opportunities to enhance refrigerator-freezer energy efficiency through the application of VIP's are significant. Published estimates of the opportunity, however, are generally wishful. Application realities such as cabinet structure needs, foam flow patterns, other assembly components and assembly or service access requirements restrict the insulation volume available for installation of VIP's.

Limited models of refrigerator-freezers containing VIP's are presently being produced in Japan and Europe. Two US manufacturers previously produced limited models containing VIP's. The current benefit-to-cost relationships for VIP's limit justification of their use to speciality applications or concepts-confirmation demonstrations. Broad-base development efforts continue, however, and further applications of VIP's are probable. Breakthrough developments in automated panel fabrication processes are considered necessary to substantively expand application opportunities.

3.2.2 Advanced vapour compression

Energy efficiency improvement in domestic refrigerator-freezers has also been achieved using advanced vapour compression cycles namely the Lorenz and Meutzner cycle using zeotropic refrigerant mixtures and the "dual evaporator" vapour compression cycle.

3.2.2.1 Lorenz and Meutzner cycle

The Lorenz and Meutzner cycle with zeotropic refrigerant mixtures offers an excellent potential to decrease energy consumption in domestic refrigerator-freezers. During evaporation or condensation of zeotropic mixtures at constant pressures, the saturation temperature changes due to differences in the volatility of the constituents of the mixture. The temperature difference between the dew point and the bubble point of the mixture at any specified pressure is referred to as the refrigerant's temperature glide. For domestic refrigeration, it is conceivable that a mixture can be chosen with an appropriate temperature glide that will accommodate the temperature requirements for both the freezer and the fresh food compartment. In order to accomplish the maximum potential for zeotropic mixtures, it is necessary to configure the refrigeration circuit in a manner as prescribed by Lorenz and Meutzner, where two evaporators and intercoolers are used to provide heat transfer in the fresh food and freezer compartments. In simulation studies, for a variety of working fluids as refrigerants, efficiency gains as high as 26% have been predicted /San91/. In laboratory experiments, gains of 15% have been realised /Zho94/, /Liu94/, although food quality at temperature levels realised has not been monitored.

3.2.2.2 Dual evaporator circuits

Several patents have been issued that deal with dual-evaporator refrigeration circuits. The idea is to have a separate refrigeration circuit for each section in a two-door refrigerator-freezer that provides refrigerant at two different pressure levels. Significant energy reductions, of the order of 20% to 30%, are predicted as a result of elevating the pressure of a portion of the refrigerant to achieve cooling in the high temperature (fresh food) section of the refrigerator rather than compressing all the refrigerant from the low pressure required in the freezer.

3.2.2.3 Refrigeration circuit with continuous capacity control

The on/off temperature control usually applied in refrigerator-freezers yields thermodynamic and refrigerant migration losses. Energy loss of the order of 10% to 20% are being reported. This can be avoided by continuous control of the compressor capacity. The continuous capacity control is possible by a frequency control in reciprocating or rotary type compressors or a swept volume control in free piston compressors.

3.3 Current use of CFC-12

Annual world-wide domestic refrigerator-freezers production figures and CFC-12 usage has been reported to be as follows from Table 3.3

In Western Europe about sixteen million refrigerators are manufactured annually. The average volume is approximately 200 litres and average charge is 140 grams per unit. For Eastern Europe, the average volume is somewhat smaller at 180 litres while the average charge is larger at 200 grams.

The North American market, influenced mainly by the US manufacturers, produces the largest unit with an average volume of 440 litres. The average charge per unit is 180 grams. In Latin America, where Brazil is the dominant producer with approximately three million units annually, the average volume is 175 litres and average charge is 180 grams.

Japanese manufacturers produce approximately 4.6 million units annually, of which 0.7 million are exported. The average size is trending upwards from 300 litres and is expected to reach 350 litres by the year 2000 as the freezer compartment becomes more common. CFC-12 usage in Japan has grown from 140 grams per unit in 1986 to 160 grams per unit in 1992.

Table 3.3 *Estimated 1992 world production of domestic refrigerators and freezers and corresponding CFC-12 consumption*

AREA	No. of Units Produced	CFC-12 Used In OEM (Metric Tonnes)	CFC-12 Used In Servicing (Metric Tonnes)
Western Europe	16,250,000	2275	80
Eastern Europe	7,500,000	1500	270
North America	9,740,000	1750	60
Latin America	5,970,000	1070	140
Asia	19,200,000	3070	460
Africa/Mid East	4,650,000	840	110
Australia	680,000	95	20
WORLD	**63,990,000**	**10,600**	**1,140**

India manufactures approximately 1.4 million refrigerators that have an average size of 165 litres, one of the smallest units produced. Each unit contains an average of 140 grams of refrigerant. The demand of refrigerators and freezers is growing fast in India.

China produced about 6 million refrigerators and refrigerated cabinet in 1992 with a consumption of CFC refrigerants amounting to 1100 tonnes. A small number of refrigerators containing HFC-152a have been produced.

3.4 New equipment

3.4.1 Alternative refrigerants to CFC-12

World-wide developments were initiated in 1988 to identify suitable replacements for CFC-12. Numerous candidates were assessed using application criteria including:

- *Environmental Acceptability (ODP and GWP)*
- *Safety (toxicity and flammability)*
- *Thermal Stability Over Anticipated Temperature Range*
- *Chemical Compatibility with Contacting Materials*
- *Low Chemical Reactivity with Contacting Materials*
- *Thermodynamic Efficiency*
- *Availability and Cost*

- ***Compatibility with High Volume Production Technology***

These intensive developments resulted in a limited selection of alternatives which are now being considered for high volume commercial application in domestic refrigerator-freezers: HFC-134a, HFC-152a, HC-600a, HC-290, HC-290/-600a blend and HCFC containing ternary blends such as R-401a, R-401b and R-409a /Kui94/. Discussions of the properties of these refrigerants are contained in section 2 of this report. A number of other single components and blends are the subject of ongoing research but are not considered to be within the scope of this discussion.

Regional differences in application criteria specification and weighing have resulted in differences in refrigerant choice. These differences are driven by variations in parameters such as historic consumer feature selections and lifestyle, government regulation, product design and construction, and supplier industry offerings. Hermetic system component design optimisation are strongly influenced by the selected refrigerant. Significant supplier industry investments are required to support the selected alternatives. These factors, coupled with optimised design investments and the extensive time and resources required to validate both component and system reliability, constrain abilities to rapidly shift from one refrigerant to another. Refrigerant selection should be viewed as a strategic decision, not an easily reversed tactical choice.

Table 3.4 presents the calculated relative performance parameters for the leading alternative refrigerants to CFC-12 for a theoretical cycle having a -25^{o}C evaporator and a +55^{o}C condenser /Kui94/. Calculated efficiencies are within a few percent for all alternatives and can be considered equivalent for the purposes of this discussion, but this is not rigorously correct. If refrigerator efficiency is a critical decision parameter, judgements should be based on experimental results.

Table 3.4 ***Refrigeration cycle properties of leading alternatives to CFC-12 for domestic refrigeration***

Refrigerant	**CFC-12**	**HFC-152a**	**HFC-134a**	**R-401a/ R-401b/ R-409a**	**HC-290 / 600a**	**HC-600a Isobutane**	**HC-290 propane**
Formula	CF2 Cl2	CH3-CHF2	CH2F-CF3	HCFC/ HFC blend	C3H8-C4H10	C4H10	C3H8
Volum.cap. (kJ/m^3),-25C	1237	1074	1185	-	1254	626	1886
Press.ratio (-25/+55C) subc. to 32 C	11.03	13.73	14.07	13.1	11.42	13.39	9.40
COP, theoret. (-25/+55C) subc. to 32 C	equal HFC-134a	> to equal HFC-134a	-	equal HFC-134a	< to equal HFC-134a	> HFC-134a	< HFC-134a
Disch.temp. Theoretical (-25/+55 C) + suct.gas cooling (pract.)	120-125 170-175	135-140 195-200	115-120 150-155	125-130 180-185	105-110 140-145	100-105 135-140	105-110 140-145

3.4.2 Primary replacement

3.4.2.1 HFC-134a

Refrigerant HFC-134a is non-flammable and has zero ozone depletion potential. This refrigerant has been extensively studied and developed and has been selected as the alternative to CFC-12 in several major markets, including North America, South America, Asia and Australia. It is expected to be applied in selective applications in every region of the world. Several international chemical companies have invested in facilities to manufacture this chemical. All major compressor manufacturers are offering models optimised for use with HFC-134a.

The volumetric capacity of HFC-134a is 12% below CFC-12 at the standard refrigerant rating conditions (-25°C evaporator, 55°C condenser) used by compressor manufacturers for performance measurements on calorimeters. The capacity loss is offset by increasing the displacement of the compressor. Efficiencies of compressors with the displacement change have been measured to be equivalent to CFC-12 compressors using similar viscosity oils. Recent energy consumption tests in refrigerator-freezers have shown that HFC-134a is approximately equal in performance to CFC-12 in optimised units /Swa94/. HFC-134a is benign and shown to be compatible in sealed tube tests in the presence of metals, oils, plastics, and elastomers common in refrigeration systems.

This refrigerant is immiscible with the naphthenic and alkyl benzene oils historically used with CFC-12. Several types of synthetic polyolester oils have been shown to be effective lubricants for use with HFC-134a. These oils are hygroscopic and require enhanced process control to ensure maintenance of low system moisture requirements. HFC-134a is a more powerful solvent than CFC-12 and may require conversion to more solvent resistant grades of electrical insulation in the compressor motor. Molecular sieve filter/dryer grades different from those used with CFC-12 are required. HFC-134a cannot be considered a drop-in replacement for CFC-12, substantive modifications are required. Typical changes for HFC-134a refrigeration systems include more restrictive capillary tubes, less refrigerant charge, and new filter dryers (XH-9).

Problems from capillary tube plugging due to sludge generation have been encountered by several manufacturers during developmental endurance testing of refrigerators containing HFC-134a. Both paraffinic motor winding lubricants and incompatible fabrication process fluids have been isolated as root causes for these problems. Observed problems have been resolved, but the application of HFC-134a is clearly more sensitive to contamination by foreign materials compared to CFC-12. Disciplined manufacturing cleanliness and process control are essential for successful application of HFC-134a.

3.4.2.2 Hydrocarbon refrigerants

Hydrocarbon refrigerants are flammable. They have zero ozone depletion potential and a global warming potential approaching zero. Their efficiency is slightly better than other leading alternative refrigerants and they are fully compatible with the lubricating oils conventionally used with CFC-12. The latent heat of vaporisation of hydrocarbon refrigerants is very high in comparison to CFC-12 and its density is approximately one third that of CFC-12 making these refrigerants attractive because of its low charge requirements and circulation rates /Mey93/. However, hydrocarbons are weaker solvents than CFC-12 which some believe could make them more susceptible to long-term sludge build-up, but no confirmations of this opinion have been reported to date. The active application efforts in Europe are rapidly expanding the data base for these alternatives.

The initiative by one German manufacturer to successfully apply hydrocarbon refrigerants in cold-wall refrigerator-freezers is being widely adopted by other European manufacturers. Approximately one million refrigerator-freezers using HC-600a/or mixture of HC-290 and HC-600a have already been marketed in Europe. Initial hydrocarbon application used HC-290/ HC-600a (propane/isobutane, 50%/50% by mass) blends. This production-level will be decreased (noise problems) or production may even be stopped; more recent introductions are only using HC-600a (isobutane) by itself which is reported to yield lower noise levels. The binary blends had the initial benefit of modulating capacity to permit their use with compressors designed for use with CFC-12. HC-290 (propane) is not presently considered a viable candidate for domestic refrigeration due to its high volumetric capacity and increased noise concerns. At this time the flammability of the hydrocarbon refrigerants precludes consideration for use in no-frost refrigerator-freezers.

Draft IEC and UL safety standards for use of hydrocarbon refrigerants in domestic refrigerator-freezers are being circulated for critique. The absence of a final standard has created some issues with certification agencies, but this is viewed as a temporary transition concern. Required purity levels for hydrocarbon refrigerants are still being debated. No concerns regarding chemical or thermal stability have been reported. Comprehensive toxicity information regarding impurities and by-products is not yet available.

3.4.3 Other replacements

3.4.3.1 HFC-152a

Refrigerant HFC-152a is flammable (although lower compared to the hydrocarbons flammability), has zero ozone depletion potential and has a low global warming potential. Chinese investigators have concluded that HFC-152a is a viable alternative for use in domestic refrigerators. It is alleged to be compatible with the synthetic alkyl benzene oils historically used with CFC-12, but necessary long term confirmation of favourable short term test results has not been reported. Inconsistencies exist among efficiency results reported by various investigators. In balance, however, results appear comparable to CFC-12 and HFC-134a. Comprehensive thermal stability, chemical stability and materials compatibility information are not available for HFC-152a, but no significant issues have been identified to date.

Limited world production capacity has been in place for several years. HFC-152a is not perceived to offer any benefit versus the HFC-134a or HC-600a alternatives being actively developed by multi-national domestic refrigerator manufacturers. Consequently, broad based developments to mature the application technology for HFC-152a are not in progress. Preparation for use must include careful and informed assessment of product design, factory processing and field service considerations appropriate for the application of flammable refrigerants.

3.4.3.2 HCFC and HCFC/HFC blends

R-401a, R-401b are three-component HCFC/HFC blends and R-409a is a three component HCFC blend. Since they contain HCFCs they do not constitute a final solution to ozone depleting substance phaseout and are not being actively pursued for new equipment manufacture by multi-national refrigerator manufacturers. This limits the maturation of application technology for the blends. Less intensive developments continue with these blends for fields service use.

Synthetic alkyl benzene oils are the preferred lubricants for use with R-401a, R-401b, and R-409a blends. However, R-409a, which contains three HCFC refrigerants miscible with naphthenic oils, can be utilised in most cases with no oil change. The naphthenic oils more commonly used with CFC-12 refrigerant are immiscible with the R-401a and R-401b blends. The absence of an oil solvent creates the potential for paraffinic wax build-up which could plug the capillary tube. To avoid this risk, it may be necessary to replace the naphthenic oils with alkyl benzene oils during the service procedure. If necessary, this would significantly complicate the procedure and introduces questions regarding the utility of the blends. This, in turn, would further reduce the rate of application technology development for these blends. Detailed developments for systems optimisation and reliability validation need to be completed prior to significant usage of the HCFC/HFC blends.

3.4.4 Refrigerant flammability

The safe application of flammable refrigerants in domestic refrigerators is a topic of current debate. Characteristic refrigerant properties for consideration are the lower flammability limit in air, the minimum energy required to ignite a flammable mixture, and the flame propagation rate after ignition. The amount of refrigerant in the system is another consideration. Two example risk situations are:

(1) A low-side leak, such as an evaporator fault, which could enable refrigerant to accumulate within the food storage compartment, potentially from a flammable mixture, and potentially be ignited if an electric arc were generated within the compartment.

(2) Open flame brazing of joints while performing service on the refrigerator.

Product configuration is a critical parameter for assessing the application risks of flammable refrigerants in domestic refrigerators. For example, the so-called cold-wall evaporator refrigerators comprise a large fraction of European production models. The sheet and tube evaporators in these refrigerators are located within the cabinet insulation space. Any refrigerant leakage must migrate through the refrigerator liner to enter the food storage compartment. This results in a reduced probability for refrigerant accumulation within the food storage compartment, as required to create the risk in example 1 above. This reduced probability has significantly influenced the acceptance of flammable hydrocarbon refrigerants in Europe. Conversely, no-frost refrigerator configurations comprise a large fraction of North American and Asian production models. These refrigerators contain high-efficiency, thin-wall aluminium evaporators having line-of-sight electric defrost heaters within the food storage compartment. This construction permits leaking refrigerant to accumulate within the food storage compartment and this also containing electrical components which could cycle and provide an arc. Substantial product redesign, possibly including new concept introductions, would be required to alleviate concerns with the application of flammable refrigerants.

The configuration examples above are in no way intended to represent definitive or comprehensive judgements regarding the application of flammable refrigerants. Each manufacturer must conduct unique hazard assessments for their specific product configurations. The intent of this discussion is to impress on the readers the need to rigorously assess their own situations.

3.4.5 Product reliability

Domestic refrigerators have outstanding reliability experience. This creates high consumer expectations for continuing reliability. Units are expected to run for 15 to 20 years without failure or service. Compressor integrity is essential to this reliability and compressor lubricant performance, in turn, is essential to compressor integrity. An example 50% duty cycle over 15 years requires more than 65,000 hours of compressor mechanism run time at temperatures significantly above ambient room temperature. For reference, an automobile being driven at 100 kilometres per hour would travel 6.5 million kilometres in this same time. This long time endurance need places critical lubrication stability requirements on the 100 to 300 millilitres of oil hermetically sealed in the refrigeration system and critical thermal stability, chemical stability and compatibility requirements on all materials contained within the sealed system. Fundamental understanding of the chemical mechanisms controlling system reactivity is necessary to appropriately design and interpret endurance reliability test programs. These mechanisms are potentially unique to each combination of materials being considered. Care must be exercised to avoid introduction of false failure modes through improper or overly aggressive accelerated testing. The extended service expectation introduces concern for extremely low reactivity rates which can be influenced by trace residue impurities such as those introduced by exposure to cutting fluids and cleaning solutions during system component fabrication and assembly. System stability sensitivity to trace impurities results in the need for disciplined attention to factory cleanliness and fluids selection.

3.5 Alternative technologies

There are a variety of experimental systems under investigation that claim improvement in efficiency using unconventional techniques that require further analysis. This list includes the following:

A. *Stirling cycle*
B. *Absorption cycle*
C. *Sonic compression*
D. *Linear compressor technology*
E. *Thermoacoustic refrigeration*
F. *Thermoelectric refrigeration*

3.5.1 Stirling cycle

Some research and development companies and appliance manufacturers are actively pursuing application of the Stirling refrigeration cycle to refrigerator-freezers. Different approaches are used in both the drive mechanism (free-piston versus kinematic drives) and bearing systems (gas versus flexible bearings) to achieve low friction losses. Two free-piston systems have demonstrated energy efficiencies comparable to conventional refrigerator-freezers. One project, a collaborative effort between two companies, used a free-piston prototype with gas bearings to achieve an efficiency comparable to vapour compression refrigerator-freezers in the 200 W range. Superior efficiencies are anticipated in the 50 W range. The second project resulted in a demonstration prototype using flexible bearings that limit the compressor stroke and provide oil-free compression and expansion with low friction. This particular design may be competitive with conventional refrigerator-freezers. Investment costs to commercialise either concept described above are quite high. A commercially viable design must be generated and validated in a time frame consistent with proper investment risk management. The lead time to do this will limit introduction into the market within the next seven years.

In general, refrigerator-freezers manufacturers' interest in pursuing Stirling technology is limited. High investment entry cost, no extended term reliability information, and no demonstrated efficiency advantage over conventional systems using HFCs are three significant reasons. Perspective could be altered if international agreements force the use of non-fluorocarbons, non-flammable refrigerants with zero GWP /AFE93/.

Integrating Stirling cooler devices into a refrigerator cabinet while maintaining efficient heat exchange between cold and hot ends of the machine is a technical challenge. Stirling system applications to small storage volume refrigerator-freezers could be favoured since refrigerant fluid constraints would similarly constrain the selection of heat pipes which may be desirable to distribute cooling in larger storage volume units. Forced convection distribution alternates avoid this constraint at the expense of increased parasitic power demand, penalising the already borderline energy efficiency of the Stirling units.

3.5.2 Absorption cycle

Absorption cycle refrigeration is a viable alternative to the vapour compression system in domestic refrigeration as there are consumer products already available in Europe based on the absorption principle.

Absorption refrigeration relies on a mixture of ammonia-water-hydrogen as a working fluid and can use either an electric heater or combustion (natural gas, LPG or kerosene) as the energy source instead of an electrically driven compression refrigerator. Small absorption refrigerators with similar cabinet load characteristics consume approximately twice the site energy as electrically driven compressor refrigerators. The primary energy consumption of the absorption unit could be less than that of vapour compression refrigerators if the absorption units have small freezers and are heated with high efficiency natural gas burners.

More than a million of these machines are manufactured and sold annually in world-wide markets and these products are commonly used in recreational vehicles because of their ability to use bottled gas and in hotel rooms because of their extremely quiet operation. These products are limited in size because of constraints imposed by the operating cycle (e.g. reliance on bubble pumps) and cannot automatically be scaled up to displace conventional compression products.

3.5.3 Sonic compression

Sonic compression is appealing as a potential low-cost, high efficiency, oil-free compressor technology. It should work with a wide range of refrigerants, including hydrocarbons, fluorocarbons and ammonia. Prototype compressors are now under construction. Theoretical COP is comparable with current vapour compression refrigeration cycles. The first prototype will have a target cooling capacity of 110 W to 250 W. With manufacturer support this technology could be in limited production within 3 to 5 years.

3.5.4 Linear compressor technology

Linear compressors are a promising high-efficiency alternative to conventional reciprocating and rotary designs. In a linear compressor a linear motor drives a piston directly without need of a crank mechanism. Use of gas bearings eliminates the need for oil. Prototypes have given COP of 1.75 (standard testing conditions) and better. Theoretically, a COP of 2 seems to be possible. The technology is currently licensed to one refrigerator compressor manufacturer and two more are completing licensing agreements. Limited commercial production is possible within three years.

3.5.5 Thermoacoustic refrigeration

A small thermoacoustic cooling unit was demonstrated on the space shuttle "Discovery" in January 1992. A higher powered unit (200 W refrigerator, 120 W freezer) is currently undergoing tests. The unit utilises inert helium/argon gas with none of the direct GWP of fluorocarbons. Thermodynamic energy efficiency as high as 20% of Carnot efficiency was measured in first generation units. The higher powered second generation unit is predicted to achieve 42% of Carnot efficiency excluding electrical losses. The thermodynamics of the technology have been demonstrated, however, the key to realising energy efficiency for refrigerator-freezer applications will be the efficient, low-cost generation of acoustic power as well as efficient coupling of the cooling engine.

The key external variable remains to be sustained funding to demonstrate the modelled competitive energy efficiency of the overall system, including secondary heat exchanger and electro-acoustic energy conversion. With adequate funding, a unit could be introduced into the market within three years due to the potential for an energy-efficient, low investment, low production cost cooling device with broad applications. The use of non-fluorocarbon inert gases could be increasingly attractive to industry and consumers given global warming concerns. The market potential of thermoacoustic refrigeration is broadly estimated as medium to good /AFE93/.

3.5.6 Thermoelectric refrigeration

Thermoelectric refrigeration is based on the observation first made by Peltier in 1834 that an electric current passing through a circuit formed by two dissimilar conductors or semiconductors will cause a temperature difference to develop at the junction of the two conductors. A refrigeration effect develops at the cold junction, and heat is rejected at the hot junction. This phenomenon provides the basis for the thermoelectric refrigeration.

Presently, thermoelectric refrigeration devices have very low energy efficiency relative to alternative technologies. The COP of the refrigerators based on this technology is almost one fourth of vapour compression based refrigerators working under similar conditions. Significant break through in materials is needed to make this technology energy efficient.

Thermoelectric cooling will continue to be successful in cooling applications where portability, size, ruggedness and reliability are more important factors than energy efficiency.

3.6 Retrofits

In current vapour compression cycles using CFC-12, the changes involved in retrofitting domestic refrigerator-freezers for alternative refrigerants must not affect the 20 year life cycle of the appliance. For alternative refrigerant field conversions, service networks are faced with limited time to train their work force in practices ensuring reliability. The most cost effective service routines will be implemented in changing from CFC-12 to alternatives that protect the environment. In principle, refrigerators that have not been designed for the use of flammable refrigerants should not be serviced with flammables, unless safe retrofit procedures have been developed.

3.6.1 Primary replacement : CFC-12

Most manufacturers will continue to service existing refrigerator-freezers by using up bulk stocks of CFC-12. There will be a depletion of CFC-12 in the near future due to usage by automotive services and chemical company production scale downs. These events will create opportunities for CFC-12 substitutes in the field service area.

3.6.2 Other replacements

3.6.2.1 Ternary blends

The use of ternary blends is going to become more common in servicing refrigerator freezers. These refrigerants are near azeotropes which closely match the thermodynamic properties of CFC-12. There is some concern that the current mineral oil charge in appliances will require replacement with alkylbenzene oils when converting to the ternary blends. The concern relates to immiscibility of HCFC-22 at low temperatures and potential flocking. The flocking condition can create waxing deposits on internal component parts which may cause capillary tube flow restrictions. Before extensive usage occurs, analysis of performance and system optimisation will be performed at manufacturers laboratories.

3.6.2.2 HFC-134a

The option of using HFC-134a as a service retrofit of existing CFC-12 charged refrigerator-freezers is not practical. There is concern that the time required, the flushing routine, and the compatibility with previous system mixtures prevents satisfactory performance.

3.7 Recovery, recycling, reclamation and conservation

3.7.1 Recovery and recycling

Recovery and recycling of refrigerant is becoming common to minimise ODS emissions to the atmosphere and to extend the availability of CFCs for servicing during the transition period. Commercially demonstrated and effective technologies are available in Non-Article 5(1) countries for the recovery and recycling of the refrigerants from refrigeration systems. Equipment for recovery is available with a wide range of features (like hand carryable, movable on wheels, etc.) and prices, with specifications that provide for recovering more 92% to 97% of the refrigerant (due to solubility in the lubricant). Recycling equipment is rated for contaminant removal capability. A variety of recycling equipment is also available over a wide price range.

Recovery of CFCs from small equipment like refrigerators is more difficult because of large numbers, dispersal and high cost of collection as the amount of recoverable refrigerant is very small and from many of the units serviced it might have leaked out.

However, it is expected that a part of the total CFC requirement to service refrigerator-freezers will be met from recovery and recycling.

3.7.2 Reclamation and conservation

The process of reclamation involves the upgrading of recovered refrigerant to restore its quality to a specified standard of performance. This can reliably be carried out only at a central facility with appropriate training and quality control.
The purity of current reclaimed CFC-12 is under investigation to determine its acceptability for maintaining the 20 year life of refrigerator-freezers. Part of this effort will entail testing by manufacturers to develop standards that identify consistent reprocessing controls to ensure appliance reliability. No established effort is in place to meet the needs of all refrigerator-freezer manufacturers. There is some question concerning contaminants and non-condensable in reclaimed CFC-12 which could cause system problems.
The conservation of refrigerant can be an effective measure to reduce the CFC requirements for servicing. The conservation of refrigerant can be achieved two ways, firstly, by adopting proper design and installation of new equipment's to minimise actual or potential leaks. Secondly, by improving service practices which will result in reduced emissions.

3.7.3 Technicians training for recovery, recycling and servicing

The service technicians can play an important role in reducing the CFC emissions provided proper training is imparted to them. The training would include a basic understanding of the effect of CFC refrigerants on the environment, hands on practice with recovery and recycling equipment's, leak testing and fixing leaks, and an introduction to environmentally friendly refrigerants. A proper way of charging during servicing would also limit the quantities of refrigerant that are used.

3.8 Forecast of usage

The phaseout of CFCs in domestic refrigerator-freezers has already begun. About one million refrigerator-freezers using isobutane or a mixture of propane and isobutane (50% by mass) as an alternative refrigerant have already been marketed in Europe. Manufacturing facilities for HFC-134a refrigerator-freezers have been already geared up in almost all the developed countries. Selected production model refrigerators using HFC-134a refrigerant have been introduced in several countries. A substantial amount of continuing phaseout in most of the developed countries will take place by the year 1995.

Considering the annual production growth rate of refrigerators (having both smaller and larger inner volumes) of more than 10% for Article 5(1) countries and 2 - 7% for developed countries, the requirement of CFCs and the alternative refrigerants have been presented in this section. The base year is 1990 /Kui91/. The recovery of refrigerant will meet part of the servicing requirements, but the total tonnage recovered will not be enough to significantly modify the data given in Tables 3.5 and 3.6.

3.8.1 CFCs

It is almost certain that most of the countries, both developed and developing, will phaseout CFC-12 in domestic refrigerators earlier than the Protocol requires. However, the rate of transition will become clearer by the end of 1994. The assumption used to generate the tables are as follows:

- 85% of the developing countries production and 15% of developed countries production will be using CFC-12 in 1995.
- By 1997, 70% of Article 5(1) production will still be using CFC-12 while all other production will be CFC free.
- By 2000, Article 5(1) production will be down to 10%.
- By 2005, there will be no CFC-12 used in production of appliances.

3.8.2 HCFCs

The amount of HCFCs in domestic refrigerators has been estimated assuming that only 3% of domestic refrigerators have their systems serviced during their life time. Thus, even if the HCFC-22/HFC-152a/HCFC-124 blend or the HCFC-22/HCFC-142b/HCFC-124 blend is widely used for servicing, use of HCFCs will peak at no more than 2% of the annual refrigerant usage. An additional 1% has been allowed for use of any HCFCs in blend applications or as straight refrigerants in new products.

3.8.3 HFCs

The HFC-134a requirement has been estimated on the assumption that 70% of the domestic refrigerator production may be converted to HFC-134a from CFC-12. The scenario will, however, become clear only by the end of year 1994. Since the density of HFC-134a is about 10% lower than that of CFC-12, the total consumption will decrease by the same amount. In addition, higher prices of the new refrigerants as well as environmental considerations are likely to result in further reduction in charging, better leak testing and also in recovery efforts. A counter trend to the before mentioned effects in larger, more efficient refrigerators with larger heat exchangers and refrigerant charges.

3.8.4 HC-290/HC-600a

It is expected that about 30% of domestic refrigerators production may be converted from CFC-12 to hydrocarbons (to mainly isobutane, and next to mixtures of isobutane and propane). The hydrocarbon requirement has been estimated considering that hydrocarbon based refrigerators will use only about 40% of the charge used in CFC-12 refrigerators.

3.9 Developing country considerations

The process of phaseout of CFCs has also been initiated in most of the developing countries. CFCs phaseout is a technically complex proposition in domestic refrigeration. Technologies for this sector have not yet crystallised even in the developed countries. Moreover, developing countries are not in a position to go in for more than one changeover. Thus to enable a smooth phaseout of CFCs in developing countries it may be desirable that these countries evaluate the available alternate technologies in their own climatic, working, and social conditions etc., so that the adopted technology may be absorbed easily. In this situation phaseout may take a slightly longer period. Still it is almost certain that in all developing countries the phaseout of CFC-12 in domestic refrigeration will be faster than the Montreal Protocol currently demands (i.e. 2010).

However, it is of utmost importance to extend technological help to the developing countries, without any commercial interest, to expedite the phaseout in new equipment and reduce inventory of CFC-12 refrigerator-freezers in these countries. This will reduce the demand of CFC-12/alternative refrigerants for servicing/retrofitting.

Table 3.5 Refrigerant usage (metric tonnes) by year 1990-1997 and country type

Ref. Type	1990			1995			1997		
	Article 5	Other	Total	Article 5	Other	Total	Article 5	Other	Total
CFCs	2200	6884	9084	3760	1450	5210	4190	0	4190
HCFCs	0	0	0	50	250	300	100	400	500
HFCs	0	0	0	530	3440	3970	1330	6900	8230
HCs	0	0	0	40	660	700	105	990	1095

Table 3.6 Refrigerant usage (metric tonnes) by year 2000-2005 and country type

Refrigerant Type	2000			2005		
	Article 5	Other	Total	Article 5	Other	Total
CFCs	890	0	890	0*	0	0
HCFCs	150	150	300	50	50	100
HFCs	6250	8540	14790	13880	11900	25780
HCs	485	1630	2115	1060	2270	3330

* Assumes Article 5(1) countries, such as China and India will meet the requirements earlier than the Protocol requires

It is useful to categorise the developing countries as those who are:

1. *Domestic refrigeration end users.*
2. *Domestic refrigeration manufacturers for their own internal needs.*
3. *Domestic refrigeration manufacturers for their own internal needs and for export to developed countries.*
4. *Compressor manufacturers for domestic refrigeration products manufactured in their own country or for export as compressors.*
5. *Aspirants to manufacture their own replacement refrigerants.*

It is necessary to identify which category/categories that developing countries fit in and the specific problems they encounter.

3.9.1 Category 1 countries

The category 1 countries will buy CFC free technology embodied in the products that they import. Their servicing infrastructure will require appropriate procedures, equipment and spares. In many cases these needs will automatically be provided through the supply chain that now supplies CFC-12 refrigeration. Help may be required to upgrade servicing skills. Retrofitting of existing population of refrigerators/freezers may be necessary as it may be difficult to meet servicing requirements of CFC-12 by recycling alone.

3.9.2 Category 2 countries

Category 2 countries will need products redesigned for new refrigerants. If the manufacturers have an agreement that provides refrigeration system design their difficulties will be minimised. If they normally perform their own system development, they should find the change manageable with some technical assistance. However, these countries will require upgradaing of servicing facilities as well as retrofitting of existing appliances since CFC-12 available from recycling may not be sufficient.

3.9.3 Category 3 countries

Category 3 countries will have to supply CFC free cabinets to their developed country customers much sooner than category 2 countries to their own internal markets since exports will have to satisfy customer country laws. These countries will also need technical assistance for finalising design changes and adaptation to manufacturing of non-CFC appliances.

3.9.4 Category 4 countries

Many of the compressors presently produced owe their origins to perhaps half a dozen highly competent compressor manufacturers with full design and development capability. Some of these second generation manufacturers now have capable design and development facilities of their own. Options for those who do and do not have technical agreements are:

- A technical agreement (probably with the company that originated the design)
- The manufacturer establishing or expanding his own design and development capabilities.
- Design and development by some national or regional research organisation.

The compressor and appliance manufacturers in developing countries can derive benefits by following the progress already made by developed countries in developing materials and compressors for alternative refrigerant. These manufacturers may, however, require to carry out some developmental work to adopt local materials similar to that specified in the literature or in the technical agreement.

3.9.5 Category 5 countries

Discussion of alternative refrigerants production is outside the scope of this section. However, manufacturing capabilities of a refrigerant by a country may effect the choice of alternative refrigerant for domestic refrigeration. Refrigerant for servicing exported products would have to be available in the customer country.

Since appliances use a very small amount of CFCs, a plant devoted to production of a refrigerant for their exclusive use may not be economically viable. It is therefore necessary for the refrigerator industry to co-ordinate its efforts with the other industries involved. In the same way, countries with low consumption (irrespective of their state of development) will have to carefully examine the economics of producing small tonnage's of complex refrigerants.

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Appendix

Processing Technology Considerations

General Concerns For Manufacturing

Conversions from CFCs to environmentally safer replacements involve significant changes that impact refrigerator-freezer manufacturing facilities and support industries such as compressors, coils, plastics, tubing, oils, chemicals and fasteners. The scope of changes relates to materials, chemicals and component process flow auditing to verify compatibility of new systems for life cycle durability and reliability. The process flow must be totally understood and reviewed to decide when changes can be made to ensure replacement refrigerant will properly function in the finished product.

Processing Technology

Following is a list of new equipment and changes, required for introducing HFC-134a, in the factories for domestic refrigerator-freezers, compressors and other related parts:

(i) New leak detectors (halogen detector) and new calibration masters for HFC-134a should be used. In addition, attention must be paid to avoid detector exposure to CFC gas. The leak detector if exposed to CFC gas, may indicate wrong value.

(ii) Moisture content in oil should be controlled at 40 ppm or less by providing an oil purifier with heaters for polyolester oil.

(iii) In-line moisture detectors (oil line audits ester oil).

(iv) Vacuum pumps and charging machines must be exclusively used for HFC-134a and polyolester oil. Refrigerant purity should be 99.95% or more, and the contamination of chloric impurity gas should be 100 ppm or less.

(v) Refrigerant and refrigeration oil compatibility of the elastomer of O-rings and sealing materials for production facilities must be verified beforehand.

(vi) Working fluid for vacuum pumps and charging machines must be prevented from penetrating into the refrigeration circuit.

(vii) Surplus vacuum pumps should be prepared in the period of refrigerant transition.

(viii) Training in brazing techniques (smaller molecule than CFC-12).

(ix) Brazing flux should be particularly specified or should not be used. Some alternatives will deteriorate refrigeration oil.

(x) Chlorine cleaning agents such as 1,1,1 trichloroethane (to be phased out in the developed countries by 1/1/1996), trichloroethylene, etc. and solvent must be used at little as possible, preferably not all (1,1,1 trichloroethylene cannot be used after 1995).

(xi) Most of the oil used for expanding tubes such as copper tubes and press oil have high total acid number. Therefore, the total acid number of the oil and the constituents and quantity of the additive should be verified. Oil must remain as little as possible. Residual oil can deteriorate refrigeration oil.

(xii) Residual machining oil, coolant, etc. can clog capillary tubes. They must be made to remain as little as possible.

(xiii) High viscosity oil such as paraffin oil, grease, wax, etc. must not be used. Residual high viscosity oil will clog capillary tubes.

(xiv) Attention must be paid not to make components gather red rust and oxided scales in the course of manufacturing.

(xv) The compatibility of cleaning agent and machining oil must be verified by measuring their total acid number and pH and by testing sealed tubes containing refrigerant, oil, potentially contacted metals and process fluids being tested.

4 Commercial refrigeration

4.1 Introduction

Commercial refrigeration is composed of a large range of equipment varying from :

- Central system where the compressors are located in a machinery room
- Stand alone equipment where the condenser unit is integrated within the equipment
- Separated (split) systems for applications such as small food preparation areas, cold rooms and process facilities

Overall, commercial systems may be defined as those where the public has an indirect contact with the refrigerating system where special regulation may exist.
The accepted definition is that the upper limit of compressor drive shaft power input per system is not greater than 150kW. There is no specific power input lower limit.

4.2 Current use

4.2.1 General position

The refrigerants used in this sector for service still include all the CFCs and HCFCs reported on in previous years. A significant quantity of these refrigerants are still applied to new systems in developed and developing countries.
There is strong economic pressure for the continued use of CFCs and HCFCs, which in part is a function of the world economic condition but is equally due to the relatively low cost and availability of these refrigerants. Another problem is the degree of uncertainty regarding the availability and success of several alternative refrigerants. This latter factor has been and still is responsible for some decision makers remaining with CFCs at present, in the full knowledge that a change has eventually to be made. The call by some to place restrictions on HFCs in addition to HCFCs even before CFCs have been abolished, adds yet another barrier.
While this attitude is in effect building in obsolescence in the long term, the attraction of lower first cost installations and simplified service cannot be ignored. Clear and unambiguous regulations from the policy makers is essential if attitudes are to be changed.
The use of HCFC based blends provide a valuable interim solution and will enable many CFC users to convert and continue their operation when CFCs are no longer available for service, with the minimum of disruption and cost penalty. This particularly applies to the CFC-12 and R-502 replacement or "alternative" blends of proven performance now commercially available. (See Tables 4.1 and 4.2.)

The improvement in supply of selected HFC blends, using various combinations of the following refrigerants, HFC-125, HFC-32, HFC-143a and HFC-134a, typically as shown in Tables 4.1 and 4.2, has enabled the appropriate design procedures and installation techniques to be developed and proven in field trials and numerous installations in several countries.
The technical information on HFCs, from such trials is readily available from Trade Associations and Technical Institutes as well as from the refrigerant producers. Improvement in information transfer on these subjects will encourage correct decisions to be made regarding the move to HFCs, in some instances it may lead to an examination of "not in kind" technologies, as an alternative to the use of HFCs.

(See tables 4.1 & 4.2 for CFC-12 and R-502 alternatives respectively)

4.2.2 Central plant - generally retail applications

Central systems generally have two or more independent systems working at two different levels of temperature :
- Intermediate (medium) temperature system operation of -10°C to -20°C to hold fresh products at core temperatures between 0°C and 6°C
- Low temperature system operation between -35°C and -40°C holding frozen products at core temperatures between -20°C to -15°C or lower.

Depending on the local regulations the level of temperature for the products could vary from the above.
Depending on the size of the installations the power and the quantity of refrigerant varies over a wide range. e.g.: hyper markets (defined by sale's area > 5000 m2) encountered in France, Spain, Italy, UK, USA and many other countries, have a typical 200 kW low temperature rack of multiple compressors with similar equipment up to 500 kW for medium temperature applications. It should be noted that the 150 kW suggested maximum for commercial refrigeration is compressor shaft input per system and not the total installed kW per installation.

In some European countries and in the USA, R-502 is a typical working fluid in existing low level temperature systems. In many areas HCFC-22 is also popular for low temperature applications and is a common choice for medium temperature use.
Central systems are also used to provide refrigerant for small to medium cold rooms, blast freezers, etc..

4.2.3 Non-central systems

These may be subdivided in two main categories :

"integral" (unitary) equipment where the cooling system is incorporated within the equipment, including compressor and condenser. Such integral equipment is charged with refrigerant in factory during manufacture.

"separated (remote) small or unitary systems" where the compressor and the condenser are separated from the refrigerated fixture. The latter equipment is typically installed by contractors who construct large numbers of installations in which the power varies from 0.5 kW to 20 kW (and even higher for HCFC-22 systems). This type of system is typically used for food and beverage conservation.
A large number of both categories utilise small hermetic compressors and use the full range of common refrigerants, including CFC-12, R-502, HCFC-22 including more recently HCFC based blends plus HFC-134a for high temperature.

4.2.4 Equipment & refrigerant quantities

Estimated quantities of CFCs and HCFCs in the "global bank" in 1994 for the range of equipment shown are depicted in the following list.

	CFC-12 (tonnes)	R-502 (tonnes)	HCFC-22 (tonnes)
Integral			
Europe	4800	2400	1000
USA	5100	3000	1400
World	12800	6500	1600
Central Systems			
Europe	5400	12000	2100
USA	45300	24000	13000
World	62400	47500	38800
Misc.			
Europe	500	1000	200
USA	600	1500	300
World	1600	3000	800
Total	**76800**	**57000**	**41200**

4.3 New equipment and alternative refrigerants

4.3.1 Central systems

4.3.1.1 HCFCs as alternative

As indicated in previous sections the selection of HCFC-22 for intermediate and low temperature applications could remain the first choice in many countries, as a simple and reliable method of moving out of CFCs. As a well tried single component refrigerant, CFC-22 remains a safe option from a technical aspect, as the design and installation skills are well established.

The higher costs and reduced reliability of compression equipment for low temperature operation plus escalating costs of refrigerant could result in a progressive move away from this position towards HFCs.

4.3.1.2 HFC refrigerant blends

The considerable advances made with HFC alternatives as a result of research and testing has resulted in a choice of available ozone benign refrigerants to replace R-502 and CFC-22 in new systems. (It should be noted that retrofitting existing HCFC-22 systems with HFC blends is by no means straight forward).

The use of single stage compression for the average commercial low and intermediate temperature application, e.g. the range from 0°C down to -40°C when condensing below 50°C, makes the HFC refrigerants in the R-400 and R-500 series attractive across the range. The use of a single refrigerant throughout the temperature range of the installation considerably assists inventory control and can provide a purchasing advantage. In this context azeotropic and near azeotropic refrigerants are proving increasingly attractive for application across the low and intermediate temperature range.

Amongst other effects, such as locating packaged equipment close to individual display cases, also the emergence of a scroll compressor for limited refrigeration applications may be another significant factor in this connection, particularly the incorporation of it in a design made to limit refrigerant charge and meet the above advantages (see also section 7, 7.3).

4.3.1.3 HFCs - initial use

The initial move away from chlorine based refrigerants has generally been in response to the environmental advantages of HFCs. Until 1993 however HFC-134a was the only HFC refrigerant commercially available. Although for many commercial uses HFC-134a was not the ideal thermodynamic or economic choice. It was used for certain intermediate (medium) temperature applications but was not generally as efficient as the CFCs it replaced, it also incurred a considerable first cost penalty.
Nevertheless HFC-134a is an important single component chlorine free refrigerant when correctly applied. For most small low temperature commercial applications, the performance is however inferior to the HFC based blend alternatives.

4.3.1.4 Future progress with HFCs

Confidence in the use of HFCs is growing and there is a general acceptance of the thermodynamic similarity with R-502 with controlled condensing temperatures especially where air cooling is inadequate. A degree of reservation remains due to an uncertainty of long term trouble free operation and to the more complicated procedures necessary when using HFCs. These include the use of polyolester oils, the basic cost of the refrigerants and oils, moisture control, plus the leakage potential and difficulty of detecting emissions. HFCs demand the highest standards during installation and regular preventative maintenance if reliable operation and freedom from excessive emissions are to realised. All of which adds to higher capital and operating costs.

To encourage the introduction of HFCs there is an urgent requirement for the compressor manufacturers to arrive at a standard polyolester oil, plus the acceptance of polyolester oils with HCFC based blends which would be a further incentive for change to HCFCs now, knowing it could be easily changed to HFCs later.

4.3.1.5 Design and installation quality

The importance of applying strict design conditions and of achieving the highest quality of installation and commissioning when using HFCs, cannot be over stressed. For example the hygroscopic characteristic of polyolester oil demands a new approach to installation and service by the refrigeration engineer. The acceptance by the user that frequent planned maintenance, leak detection, moisture level checks etc., are essential to ensure reliable operation is equally important.

4.3.2 Non-central systems - detail

4.3.2.1 Practical limitations

The above comments also apply to this class of equipment, there are however additional difficulties with hermetic equipment to be addressed especially in areas with high ambient temperatures.

If a failure is to be rectified without the major difficulty of changing the oil, some type of chlorine based refrigerants may be used.

The change from CFCs and/or HCFCs to HFCs refrigerants will likely be achieved on a wide scale as a result of the introduction of new equipment depending upon the economics.

The practical difficulties encountered when attempting to retrofit HFCs in this type of equipment is well documented and is generally discounted in this report.

The failure of an existing system calls for a replacement in most instances or the repair and recommissioning of the system using CFCs as is the case with domestic refrigeration; retrofits are however becoming easier using HCFC-22 containing blends.

4.3.3 Alternative techniques & not-in-kind (NIK) techniques

4.3.3.1 Central plant - secondary refrigerants

The use of alternative techniques include the application of secondary refrigerants in both intermediate and low temperature systems. These are increasingly being considered by users and are currently being applied to an increasing number of large and small commercial installations. Operating experience with such systems, particularly at low temperature, is being developed often as a result of trial installations. This particularly applies to a small number of applications in supermarkets.

Applications range from supermarkets to large cold stores and warehouses. This approach has been encouraged by the development of proprietary secondary refrigerant fluids which are preferred to the more traditional mixtures for low temperature operation.

These new systems, particularly those incorporating plate heat-exchangers, have the added advantage of operating with a reduced primary refrigerant charge.

4.3.3.2 Ammonia

The possible use of other refrigerants such as ammonia should not necessarily be associated with commercial secondary refrigerant systems, as there remain many barriers to this fluid from several aspects including safety.

It is also important to recognise the very special care that must be taken in the safe design and application of ammonia systems, also to the training and skill of the installers and operators. If ammonia systems are not correctly described and installed these is greater risk of danger than from incorrectly installed haloncarbon systems and is important not to consider otherwise.

As alternative to toxic or flammable primary refrigerants it might be appropriate to use halocarbon primary refrigerants in low charge systems in association with secondary refrigerants

Ammonia does however remain as an effective alternative refrigerant for specific applications and its use should be encouraged for appropriate applications. It must be correctly applied and in a safe location, such applications do exist, which until now have traditionally used CFCs or HCFCs refrigerants. However, it would not normally be recommended where high occupancy or proximity to areas normally associated with public occupancy applies.(see Table 4.3, "Alternative refrigerant systems")

More detailed information about ammonia applications and properties can be found in section 5.

4.3.3.3 Hydrocarbons - non-central systems

Interest in hydrocarbons refrigerants continue to grow in some quarters, although this is generally limited to domestic sized system with extremely small refrigerant charges (50 to 100 g). Training for engineers and appropriate safety standards must be made widely available before even these small quantities are considered for commercial equipment.
Applications using hydrocarbons refrigerants in the commercial range covered by this section have yet to be developed and proven, notwithstanding the considerable debate on acceptable safety standards in many countries not only with regard to public presence but also to servicemen.

4.4 Existing equipment

4.4.1 HCFCs as the alternative - general

The application of single component HCFC-22 as an alternative to CFC-502, if not correctly applied particularly for low temperatures, can cause operational problems when retrofitting or operating it in new systems.
Many low temperature systems cannot be converted to HCFC-22 and this includes a large number using the smaller hermetic and semi-hermetic compressors, which additionally may also be unsuitable for a retrofit to an HFC.
The additional cost of providing a suitable compression process for low temperature operation must be identified when the all important planning and budgeting process is undertaken.
When considering new equipment the User and Contracting Industries have generally approached the problem of removing CFCs in a responsible manner. The use of HCFC refrigerants, mainly HCFC-22 is common, notwithstanding the above comments on cost. Many consider this to be the correct route for the immediate future and preferable to real problems associated with the introduction of polyolester oils and HFC refrigerants in existing systems. This is true in many parts of the world where for existing systems the suggested move to HFC refrigerants is viewed with suspicion and uncertainty.

4.4.2 Central plant - retrofitting

4.4.2.1 Retrofitting, HCFC based blends and HFCs

Technology and some experience to date shows that retrofit/service blends containing HCFC-22 can be applied successfully.
The lack of adequate technology in some countries could have an influence on the recommendation made as to the most suitable refrigerant for a given application. In general the aim should be to retain the CFC removed from a system, for future service use. Simple but thorough routines should be established and applied within the limits of available local skills.

4.4.2.2 Planning & budget

What ever the decision, a strategy is essential to provide detailed and constructive planning of any action which will lead to the avoidance of any reliance on CFCs and ultimately HCFCs.

The budget prepared for the retrofitting of an existing CFC system to a HCFC based blend, or straight HCFC-22, will show that the costs can be high, especially when a low temperature system is included.
Typical costs for medium sized supermarkets range from $40 to $60 per kg of refrigerant, when changing out from CFCs to HCFCs in an intermediate temperature systems. The range in cost being a function of the change out of equipment that is found to be necessary.

4.4.2.3 Survey & service support

A detailed survey of existing equipment and the preparation of a detailed inventory, including equipment condition is essential and will provide a basis for the initial planning.
At this time a decision on the most appropriate available alternative refrigerant best suited to the available technologies and local skills can be made. This should take into account reuse of the CFCs removed in the retrofit process thereby prolonging the life of the most essential equipment still using CFCs.

It is important to establish a technical rapport with the refrigerant and oil supplier and to form a partnership which can continue throughout the transition to new alternative refrigerants.
It is also essential to plan the retrofit procedures in great detail including the supporting services, availability of trained personnel, equipment and instrumentation requirements, leak detection strategy and training of existing and any new staff.

4.4.2.4 Refrigerant conservation

The availability of recovery and recycling facilities suitable for the refrigerant and for facilities for the testing of refrigerant and oil must be considered at this time.

Where skill levels and technical back-up support is inadequate, the introduction of HCFC based blends which require the minimum system change, could be advantageous. As already identified, the removal of CFCs during a retrofit can make them available for continued use in existing systems. This action will prove to be particularly important when the demand for CFCs exceeds supply.

4.4.3 Non central systems

(cross reference with section 4.3.3.1 and 4.4.2.1.)

4.5 Conservation of refrigerant

4.5.1 General position

The deliberate release of refrigerant for whatever reason is now illegal in many countries. This applies whether it occurs during a service operation, during the repair following a break-down or any similar situation, but especially during activities such as retrofit and decommissioning.
Unintentional leaks are however the main cause of emissions and can occur from a number of sources. For example from compression joints, (flare connections) shaft seals, screwed connections, service valve glands etc., through to continuous leaks from

flexible hoses. For any refrigerant it is essential that the designer selects the correct components and materials.

4.5.2 Action recommended to retain refrigerant

All actions taken to ensure that refrigerant is retained within a system should be given the highest priority and the full support of users and contractors. Service engineers have a special responsibility to follow approved procedures which are established to minimise loss of refrigerant during service and maintenance, but in particular when attending to breakdowns.

The majority of causes for emissions have been identified and steps can be taken to limit them, but these action do have a cost penalty which in the first instance may be significant.

An obvious opportunity to check for emissions is during planned preventative maintenance and/or as part of a regular leak detection programme associated with it.

In many cases the only engineering attention a system receives is in response to a breakdown, where emergency service is required and in consequence a "form" of maintenance is provided. Where routine inspections do not exist there is a greater possibility that emissions to atmosphere will continue unabated.

There is unlikely to be a significant change to this situation until a shortage of supply exists and the first cost of replacement refrigerants, particularly CFCs, becomes prohibitive.

4.5.3 Action to minimise leakage

The present average annual leakage rate world-wide in commercial installation is estimated to be approximately 20 to 25% of the operating charge. If allowed to continue unchecked this will absorb a large proportion of the refrigerants placed on the market, including HCFC blends. In particular as the HCFC refrigerant bank increases the growth in the use of new HCFC refrigerants to replenish existing systems will automatically reduce the quantity available for new systems. (mainly HCFC-22). This will have the effect of introducing an unwanted and unnecessary "control" on new HCFC (HCFC-22) systems, although one should realise that application of HCFCs in new equipment will gradually diminish over the coming years.

Recent studies have shown that leakage from operating systems is not predictable and does not follow a regular pattern. The location of leaks therefore becomes an uncertain process, in addition the majority of refrigerant leaks are small. Small leaks build up to represent a large proportion of the annual system leakage, most of which could be prevented if regular maintenance and system leak detection were introduced.

4.5.4 Refrigerant leak detection

Routine leak detection can be enhanced with information obtained from permanently installed leak detection equipment. The data provided does not locate the exact position of emissions but can direct the engineer to problem areas which might otherwise remain undetected. The operation of automatic controls, for example to ventilate areas in the event of unacceptable levels of refrigerant, is another of the many benefits of such systems.

4.6 Developing countries

Commercial systems include a large quantity of CFC-12 equipment in all types of applications ranging from cold rooms to ice makers. There is a thriving local repair and rebuild activity in most countries using local skills, engineering knowledge and assistance from second-hand imported equipment. All of these require the use of CFCs refrigerants. Much of this equipment will be beyond conversion to CFCs alternatives owing to its condition and problems of recovery equipment availability, oil, etc.

The use of ice from ice makers using integral condensing equipment as well as central systems has an important role in the maintenance of the cold chain in many countries. The eventual change from CFCs to alternatives in this equipment will demand special action.

An example of the action required is to institute a program which will cover the following:

Retention of refrigerant in existing systems, the safe recovery of refrigerants during service, repair or replacement, efficient recycling of used refrigerant coupled with realistic training of operatives and the ready availability of appropriate equipment.

Technology transfer covering the practical difficulties identified above in section 4 is seen to be critical in the anticipation of successful conversion from CFCs and ultimately HCFCs in this area.

Acknowledgements

Many thanks are indebted to J. Sainsbury plc (UK), Ecole des Mines Paris (F) and Copeland Corporation (USA) for their support in the preparation of this section on commercial refrigeration.

Table 4.1 Theoretical performance comparison of selected substitute refrigerants for CFC-12

Theoretical	Performance Comparison of Selected Substitute Refrigerants for CFC-12								
Refrigerant Type	CFC-12 single	HCFC-22 single	R-401 A Nr Azeotrope	R-401 B Nr Azeotrope	HFC-134a single	R 152a single	R-405A Azeotrope	R 717	R-409A Azeotrope
Relative Capacity	1.0	1.59	1.09	1.16	0.94	0.97	0.98	1.74	1.08
Relative COP	1.0	0.96	0.99	0.98	0.97	1.01	0.96	0.98	1.01
Discharge Temp Difference C	0	+ 17.4	+ 7.7	+ 9.7	- 3.7	+ 9.4	-3.2	+ 84	+5
Lubricant	MO	MO	AB	AB	PO	PO	AB	MO	MO + AB
Conditions +6.7 deg C Evaporation, 48.9 deg C Condensing. Return Gas 18 deg C, Isentropic Efficiency 1.0									

Table 4.2 Theoretical performance comparison of selected substitute refrigerants for R-502

Theoretical Performance Comparison of selected Substitute Refrigerants for R 502											
Refrig. type	**R717 single**	**R-502 Azeotp**	**HCFC-22 single**	**R410A near Azeotp**	**R-402A near Azeotp**	**R-403B near Azeotp**	**R-404A Azeotp**	**R507 Azeotp**	**R-407A near Azeotp**	**R-407B near Azeotp**	**R408 A**
Relative Capacity	0.89	1.00	0.95	1.37	1.08	1.07	0.99	1.01	0.92	0.96	1.01
Relative COP	0.99	1.00	1.04	0.93	0.95	0.95	0.95	0.94	0.99	0.95	1.00
Disch. Temp Difference C	+150.7	0	+32.9	+28.1	+1.0	-1.7	-6.4	-7.2	+10.2	-0.9	+2.4
Lubricant	MO	MO	MO	AB	AB	AB	POE	POE	POE	POE	MO/AB
Remark	needs inter cooler	none	needs inter cooler	needs inter cooler	none	none	none	none	none	none	none
Conditions -31.7 deg C Evap,43.3 deg C Cond, 18 deg C gas return, Isentropic Efficiency 1.0,											

Table 4.3 Alternative refrigerant system options compared with operating temperature bands

Alternative Refrigerant System Options Compared with Operating Temperature Bands

Temperature Range	Equipment size Power	Present Use CFC-12 R-502 (Typical)	HCFC Option New/retro	HCFC Option Cost Hi / Lo	HCFC blend Option New/Retro	HCFC Blend Option Cost Hi/ Lo	HFC Options
Intermedte up to -15 deg C Evaporatn	Up to 5 kw	Yes no	New No Retro Poss	New N/A Retro Hi	New Yes Retro Yes	New Hi Retro Hi	New Yes Retro Yes
Low Temp down to -40 deg C		Yes Yes	New Poss Retro No	New Hi Retro N/A	New Yes Retro Yes	New Normal Retro Hi	New Yes Retro Yes
Intermedte up to -15 deg C Evaporatn	5 kw to 150 kw	Yes Yes	New Yes Retro Yes	New Hi Retro V/Hi	New Yes Retro Yes	New S/Hi Retro Hi	New Poss Retro Not recommend
Low Temp down to -40 deg C Evaporatn		No Yes	New Yes Retro Yes	New Hi Retro Hi	New Yes Retro Yes	New Normal Retro Hi	New Yes Retro Poss

5 Cold storage and food processing

5.1 Introduction

Cold storage and food processing is one of the most important applications of refrigeration. A wide variety of applications is covered, especially if cold storage is not restricted to the cold storage of foods and if food processing is extended to cover such fields as brewing and fruit storage. No other preservation technique retains the product in a condition so similar to fresh product. Other preservation techniques such as freeze drying, pasteurisation and irradiation also require refrigeration for best application. At present there is no viable alternative to the use of refrigeration if large quantities of food are to be maintained in a condition which, at its best, is indistinguishable from "fresh".

There is potential for considerable overlap between this section and sections 4 and 6 - Commercial Refrigeration and Industrial Refrigeration. An attempt to minimise this overlap will be made by concentrating on the cold storage of food and by restricting coverage to long-term storage and distribution while ignoring the retail aspect of food storage and display. Distribution as it relates to refrigerated transport is covered in Section 9. Product such as cheese, fish or fruit may be stored at temperatures above freezing. Other product, such as "chilled" meat, may be stored at temperatures slightly below the freezing temperature of water whereas "frozen" foods are generally stored in the temperature range of -18°C to -30°C. Food processing, which includes freezing, may take place at air and refrigerant temperatures down to -40°C and lower. Certain fish products intended to be eaten raw are stored at temperatures even lower than -50°C.

The annual production of frozen food world-wide is about 27.5 million metric tonnes (1992), which is only a small part of the total volume of food products preserved by refrigeration. More than half of this is consumed in the USA. Japan has a much lower consumption while other developed countries have consumption's between that of Japan and the USA. The amount of chilled food supplied is about 10 to 12 times greater than the supply of frozen products. Improved methods of distribution and display have resulted in an increased market share for chilled "fresh" food as opposed to frozen food. Despite that, it is expected that freezing of food for human consumption will increase significantly in the developing countries to minimise food wastage. If the transport and distribution infrastructure of the developing countries improve to match that of the developed countries it is to be expected that the ratio of frozen to chilled produce will stabilise at about the same proportions.

There is no reason to doubt the estimate of the 1991 assessment that the market for food refrigeration should increase at between 2 and 3% per annum. The increase should be proportional to increases of world standard of living. The size of the refrigeration market within the sectors considered is roughly estimated at US$ 3,000 - 5,000 million annual turnover. The market share of regulated refrigerants is below US$ 1,000 million and is declining.

Table 5.1 Frozen food consumption - 1992

Country	Total Frozen Food Consumption (thousand tons)	Per Capita Frozen Food Consumption (kg)
U.S.A.	16.184	63,5
UK	2.248	39,2
Germany	2.125	26,5
France	1.967	34,1
Japan	1.903	15,3
Italy	730	12,9
Spain	708	18,2
Sweden	322	37,5
Netherlands	319	21,3
Denmark	257	49,5
Belgium	185	18,5
Austria	179	23,0
Switzerland	176	25,5
Norway	112	26,6
Finland	92	17,8

5.2 Current use

The pattern of usage has changed rapidly in the period between the production of this assessment and the previous one. There has been a very significant return to the use of ammonia for large-scale chilling, freezing and cold storage systems. This trend has been less marked in USA and Japan compared to the rest of the world but this should be seen in the context of at least 80% of refrigerated warehouses in USA already operating with ammonia. Legal and liability concerns inhibit the further adoption of ammonia in USA. Densely populated countries like Japan have difficulty in adopting the widespread use of ammonia. In France in 1991, administration-owned storage's were equally divided between the use of HCFC-22, R-502 and ammonia /AAF/.

Strenuous efforts have been made to reduce ammonia charge in large systems. In systems with temperatures between -20 and +5C, it is possible to reduce dramatically the charge of ammonia by using plate-type heat exchangers and secondary refrigerants. However, in large-scale cold storage (warehousing) and in freezing systems, ammonia will continue to be used with pumps and large charges (e.g. 8 kg per kW at -40C). In non-centralised systems, new design is proposed: low pressure receivers without circulating pumps. However, this type of design does not seem applicable for centralised systems.

Table 5.2 Estimated refrigerant consumption for cold storage and food processing

Refrigerant	**Estimated consumption** (tonnes/year)
CFCs	< 28,500
HCFC-22	> 25,000
Ammonia	> 78,500

5.3 New equipment

HFC-134a is widely regarded as an acceptable replacement for CFC-12 in new equipment but CFC-12 was not widely used in cold storage and food processing because it required considerably greater compressor swept volume than ammonia or HCFC-22 to produce the same refrigerating effect. HFC-134a also has a slightly higher boiling temperature than CFC-12 and is therefore likely to operate at sub-atmospheric pressures in some applications. This is particularly important for low temperature refrigerated transport. It is therefore unlikely that use of HFC-134a will be significant in cold storage and food processing.

HCFC-22 and R-502 are much more widely used in cold storage and food processing than CFC-12. There is no single component substitute for these refrigerants at present. A variety of blends more or less replicating the properties of R-502 are on the market. Some research has raised concerns over whether these alternatives are as efficient or as widely applicable as the refrigerants they are intended to replace /Gil3/. Where ammonia is unacceptable for legislative or safety reasons it will be possible to find a refrigerant blend suitable for the purpose, however such blends are being increasingly criticised because of their direct global warming potential. It is theoretically possible to produce more efficient blends but they would have to contain low molecular weight substances with much higher critical temperatures than the substances presently being used in R-502 replacement blends.

5.3.1 Ammonia

Ammonia is a naturally produced chemical (1,000 to 3,000 billion tonnes annually by living mammals' bacteria etc.). Ammonia for refrigeration is commercial produced from its constituents. Ammonia has no ODP and no direct global warming potential. The main limitations to the use of ammonia in refrigeration are its toxicity and flammability. Ammonia can be smelled at concentrations of less than 5 parts/million and the threshold limit value (TLV) for continuous exposure is 25 ppm. Concentrations of above about 100 ppm are intolerable to normal individuals but are not dangerous. Concentrations of over 1,700 ppm are dangerous and concentrations of over 2,500 ppm are lethal. It is worth noting that the lethal concentration of ammonia is very much less than the lower limit of flammability, which is about 160,000 ppm. The toxic and irritating effects of ammonia are much more relevant to safety than its flammability. Ammonia is difficult to ignite. Ammonia fires rarely occur on systems which have been designed, installed and operated in compliance with normal national refrigeration safety codes.

Despite the fact that there are many operating ammonia systems which are old and in poor condition, ammonia accidents are rare. However, ammonia should not be treated lightly. It is an unpleasant substance which is very dangerous in a confined space if not handled properly. Existing safety codes are adequate to reduce the risk when using ammonia systems to negligible proportions.

When designing new ammonia systems, care should be taken to minimise the operating charge and to divide, if possible, the total installation into several parts so that the amount of ammonia vented following a serious leakage can be minimised. A refrigerating system consists of several vessels, volumes and other spaces - it is not one storage vessel - and it is impossible to release the total charge instantaneously. In the worst scenario some 25 to 30% of the charge may be released over a period of time, minutes or hours. Methods for limiting ammonia charge include the use of plate-type heat exchangers as condensers using water and a cooling tower for heat rejection. Another method of limiting ammonia charge is to use a pump-less overfeed system of the low pressure receiver type. Recent papers indicate that low pressure receiver systems are possibly the only practical method of producing stable and reliable ammonia refrigeration in plants which are too small to justify the use of pumped circulation /Nes94/, /Nei94/, /Pea93/.

Ammonia is more efficient than halocarbons in refrigerating systems because of its excellent heat transfer properties and its low molecular weight. In the past however, this effect has been masked by the use of mineral oils as lubricants in ammonia systems. Ammonia is sparingly soluble in these oils which can form a serious impediment to heat transfer. Two new developments have made dramatic improvements in this situation. Insoluble poly-alfa-oleofin oils of very low pour point and high viscosity index have been introduced. These oils are very stable and do not form sludge in the presence of ammonia. Experiments are also being carried out with poly-alfa-glycol oils which are soluble in ammonia and would also have much less effect on heat transfer than mineral oils. Significant improvements in performance can be expected when these oils are generally accepted. It is too early to say how they will be applied but it is possible that PAO oils will be favoured for screw compressors where they will seal the rotors better and poly-alfa-glycol oils will be favoured for reciprocating compressors where oil return to the compressor from the system has been a major benefit of halocarbon systems.

Lightweight stainless steel tube, aluminium fin air coolers have been developed for use with ammonia. Though not so robust as the traditional galvanised steel finned coolers these air coolers are significantly lighter, therefore easier to defrost. They are also more easily supported from the cold store structure. Aluminium tubed, finned air coolers have been available for use on ammonia for many years.

5.3.2 HCFC-22

At the time of the last assessment it was felt that there might be significantly increased usage of HCFC-22 for cold storage and food processing. This trend has not materialised, partly because phaseout dates for HCFC-22 have been introduced and there is a suspicion that the final phaseout date might be brought forward as it has been for CFCs. However, HCFC-22 is being used extensively as an option in the U.S. and Japan, and, as previously mentioned, it has been used in 1/3 of the administration-owned installations in France.

The selection of HCFC-22 for new equipment instead of CFC-12 or R-502 is likely to produce a reduction in system reliability. This is because HCFC-22 gives higher discharge temperatures than either CFC-12 or R-502 and is also more chemically reactive than CFC-12. For low temperature applications which could have been carried out using single-stage R-502 systems it would generally be necessary to use two-stage HCFC-22 systems. This increases the cost and the complexity of the system.

5.3.3 HFCs

HFC-134a has been widely regarded as an acceptable replacement for CFC-12 in new equipment. The technology for HFC-134a is considered to be mature and it has gained a share of the market in certain applications. For many cold storage and food processing purposes, HFC-134a is not considered an ideal candidate because of the slightly higher boiling temperature than CFC-12.

HFC blends have been developed as replacements for R-502. These blends contain HFC-125, HFC-143a, HFC-32, and HFC-134a. These blends are available in limited quantities, and the technology is not currently considered to be fully mature. Some concerns associated with the use of these blends include refrigerant cost and leakage potential. HFC blends for the replacement of HCFC-22 are currently under development.

5.3.4 Other refrigerants

It has been suggested that "natural refrigerants", such as hydrocarbons, carbon dioxide and water, might have a role to play in cold storage and food processing. The hydrocarbons are already playing a role in blends and in domestic refrigerators. However their flammability would restrict their use to small sealed systems. It is proposed that quantities of up to 1.5 kg of flammable hydrocarbons should be allowed in Category A occupancies /Ano93/. Because of the different liquid densities this is equivalent to about 4.5 kg of CFC-12, which could be the charge of quite a large system, say 30 to 40 kW refrigerating effect.

Propane and isobutane have been tested in Europe in systems with charges of 10 to 15 kg. The installation of the equipment has been in accordance with existing codes for flammable refrigerants.

Other writers have suggested that carbon dioxide should make its return as a refrigerant. Carbon dioxide cannot be used efficiently in a conventional refrigerating system because of its low critical temperature (30.6°C). However it could very efficiently be used as the low stage of a cascade refrigerating system for product freezing. It could also be used as a secondary refrigerant either as a high pressure brine or as a volatile secondary refrigerant. The low toxicity of carbon dioxide makes such use attractive and the very small pipe sizes which would result could make such installations economic /Lor94/, /Pea92/.

It has also been proposed that single-stage CO_2 systems could be used for high temperature refrigeration in a super critical cycle. This application is unlikely to be efficient enough for use in the food industry but, where different cold storage constraints apply, such a system might be practicable.

5.3.5 Alternative technology

It is not believed that alternative technology will play any important role within the time frame considered.

5.4 Retrofits

Large systems for cold storage or food processing can have a very long useful lifetime. There is therefore a need to retrofit acceptable refrigerants into existing CFC systems. Fortunately there are few large systems operating on CFCs but there are many operating on HCFC-22, which is an HCFC, and some on R-502, which is a mixture of HCFC-22 and CFC-115.

Retrofitting can be done in a number of ways. The simplest procedure is to use a "drop-in" replacement refrigerant. Unfortunately, genuine drop-in replacements which are capable of operating without a lubricant change and of giving similar or better properties than the target refrigerant, are rare. Most genuine drop-in refrigerants contain an HCFC and/or a hydrocarbon to promote oil return.

Replacement refrigerants are not genuine "drop-ins" because they require some system changes and probably a change of lubricant but in general they are compatible with the materials of construction and give roughly the same amount of refrigeration per unit swept volume of compressor. On this basis, HCFC-22 could be considered as a replacement for R-502 under certain circumstances though it should be expected that reliability would be reduced because of the higher compressor temperatures which would result from using HCFC-22. Though satisfactory replacement blends exist for new equipment it is not clear whether any of the zero ODP blends can be recommended as particularly convenient as replacement refrigerants for existing HCFC-22 systems. The appropriate retrofit action will be determined largely by the condition of the system and local and national regulations.

Retrofitting from a halocarbon refrigerant to ammonia introduces a further degree of difficulty and would require careful consideration and considerable expense.

5.4.1 Ammonia

Retrofit to ammonia is possible in large systems where the piping and coolers are made using steel or aluminium but such systems are rare and would probably not comply with ammonia safety regulations. One possible method of retrofitting an extensive copper-piped system to ammonia would be to use a packaged ammonia refrigerating system to produce binary ice slurry in a antifreeze solution at the appropriate temperature. This solution being non-corrosive and having latent heat capacity could be circulated to the existing copper pipes and copper aluminium coolers. This method of retrofit to ammonia will become more difficult as the operating temperatures decrease and energy consumption is likely to be a problem.

5.4.2 HCFC-22

The value of HCFC-22 as a retrofit refrigerant will depend greatly on the country in which the refrigerating system is situated. When an HCFC-22 retrofit for an existing R-502 system is not feasible, the preferred route appears to be to use a retrofit blend containing HCFC-22 which is a replacement for R-502 without significant modifications of the system.

HCFC-22 can be used as a retrofit for CFC-12 providing the compressor capacity can be reduced by about 30% and provided compressor temperatures do not become too high. Compressor capacity reduction is easy for belt-driven machines, difficult for direct-coupled machines and almost impossible for semi-hermetic compressors.

5.4.3 R-502 replacement blends

R-502 has a significant niche as the preferred refrigerant for small, low temperature cold stores which can be operated single-stage. It has not been found possible to replace R-502 with a single substance. Very good approximations to the performance of R-502 have been achieved by the use of certain refrigerant mixtures. The most commonly used transitional substances are R-402 (HFC-125/HC-290/HCFC-22) and R-403 (HC-290/HCFC-22/FC-218). These substances are transitional because they contain HCFC-22. HC-290 (propane) is added to improve the return of mineral oil or alkylbenzene lubricant. The near-azeotropic nature of R-403 allows the addition of a higher proportion of propane without causing flammability to be approached which, according to some sources /Gil93/, /Sne93/ /Cro93/ makes it significantly more easy to apply than other blends.

Zero-ODP blends have also been developed and it would seem that these would be more appropriate for new equipment than the transitional blends. Such blends include R-404 (HFC-125/HFC-143a/HFC-134a) and R-407 (HFC-32/HFC-125/HFC-134a) which both contain HFC-134a as a component. Due to the low critical temperatures of the blend components these mixtures do not produce efficiencies as high as the single component refrigerants such as HFC-134a. They have also been criticised on account of their direct global warming potential.

HFC-125 is a good replacement for R-502 and HCFC-22 provided the condensing temperature can be kept below about 35°C.

5.4.4 Refrigerant conservation

Refrigerant reclaim still represents less than 3% of refrigerant sales. It is to be hoped that a certain amount of recovery and re-use is taking place at site but it is impossible to quantify this.

National legislation, making it illegal to vent refrigerants, has been enacted in many countries and is probably having a beneficial effect on the behaviour of refrigerant servicemen. However, the major constraint will be scarcity and increasing costs of refrigerant.

5.5 HCFC requirements

The most promising alternatives for HCFC-22 are the variety of replacement blends which have been produced by the chemical companies. It is too early to say which of these blends will gain general acceptance, however, R-404a and R-507 are two of the most likely candidates currently in use. Because these blends contain HFCs, there is some concern regarding their direct global warming contribution. However, their energy efficiency is considered to be good, and adequate refrigerant containment should limit the direct global warming impact.

5.6 Developing country considerations

Ammonia is the most commonly used refrigerant for medium to large sized cold storage and food processing refrigeration systems in the developing countries. However most small systems operate on halocarbons because they are simpler to install and require less training to operate. There is a need to extend the availability of ammonia equipment to smaller systems and to develop simple and economic methods of using ammonia in these systems. Ammonia refrigerating systems are not necessarily high-tech. Their safe operation requires skill and experience but not necessarily a high degree of education. Such systems are therefore very suitable for use in developing countries where many intelligent people have not had access to higher education.

There will be a temptation to use hydrocarbons as substitutes for halocarbon refrigerants as problems of cost and availability increase. Use of hydrocarbon refrigerants may increase the danger of fire or explosion, however hydrocarbon refrigerants can safely be used if the refrigerant charge is kept small and appropriate safety precautions are observed.

5.7 Forecast of use

Since the 1991 assessment, several facts have become apparent. Phaseout dates and, in certain regions, restrictions on use have come into force for HCFC refrigerants. Phaseout dates for CFCs have been accelerated. As a result there has not been such a significant swing to the use of HCFC-22 as had previously been assumed.

It appears that the amount of refrigerant required to replenish systems is proportionately much greater than had been previously assumed. This lost refrigerant is not available for recycle and reuse in existing equipment as was anticipated earlier. This has increased concerns over whether adequate supplies of halogenated refrigerant will be available to meet existing needs. There are clear signs that there is going to be a shortage of CFCs in developed countries and there are indications that the illegal import of CFCs from developing countries may become a significant problem unless stern action is taken.

In the case of forecasting refrigerant usage there are difficulties caused by, for example, concealment of the amount of refrigerant which is actually leaking from existing systems. Refrigerant recovery has still not reached the 3% of production figure and it is possible that it will never increase in absolute terms though, when production ceases, it will be the only source of CFCs.

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Appendix 5.1

Refrigeration in the Food Supply Chain

1. **Industrial Chemical**
   Fertilizers
   Gas Liquefaction

2. **Industrial Food/Drink - Food Processing**
   Cold and Chill Storage
   Brewing and Soft Drinks
   Meat
   Poultry
   Fish
   Dairy
   Chocolate and Confectionery
   Fruit - Vegetables - Flowers, CA - Storage
   Potato Products
   Edible Oils
   Bakery/Biscuits
   Agricultural
   Ready Made Food
   Other Food Products

3. **Air Conditioning**
   General need in all places where perishable food is processed, handled or stored for short term.

4. **Heat Pumps**
   Energy recovery in Food Processing

5. **Transport and Distribution**
   Refrigerated Lorries and Vans
   Refrigerated Containers and Small Cabinets
   Refrigerated Ships

6. **Large Retail**
   Supermarkets
   Freezer Centres
   Department Stores

7. **Hotels and Catering**
   Pubs and Pub Food
   Fast Food Chains
   Restaurants
   Hotels
   B & B/Guest Houses
   Canteens
   Catering

8. **Small Retail**
   Shops

Bakery
Butchers/Delicatessen
Chocolate Shops
Fish Shops
Greengrocers
Ice Cream Shops
Dairy

9. Domestic
Home Freezers/Refrigerators

Appendix 5.2

Table 5.3 *Physical properties of ammonia*

Melting temperature (1)	-77.7°C
Boiling point (1)	-33.4°C
Density	
liquid @ -33.4°C(1)	0.682kg/l
gas @ -33.4°C(1)	0.889kg/m^3
gas @ 0°C(1)	0.771kg/m^3
Ignition temperature	651°C (per DIN 51794)
Thermal disintegration	Over 450°C
Dangerous disintegration product	Hydrogen
Flammable concentration in air	15% - 28% volume(2)
Dangerous reaction	Acid creates strong neutralising and strong heat development
Other dangers	Attacks copper and zinc as well as their alloys
Molecular weight	17.032
Critical temperature	133°C
Critical pressure	11.42 MPa
Latent heat at -33.4°C(1)	1.370 kJ/kg
Relative gas-density to dry air at 0°C(1)	0.6
Solubility in oils	Slight in mineral oils/soluble in PAG lubricants

(1) at 1.103 bar

(2) **Ammonia cannot burn in outdoor conditions without a supporting flame or catalyst. Ammonia can only burn in a confined space.**

Appendix 5.3

Table 5.4 *Physiological effects of ammonia*

Gas concentration	Effect on an unprotected human being	Time
25	Smell is picked up by most people, more easily at low temperatures. At under 0°C lower concentrations (approx. 5ppm) can be picked up.	Unlimited
50	Smell is very distinct. People react and want to get away from the area.	8 hours work per day and week is permitted in most countries
100	No dangerous effects on healthy people. Unpleasant, may cause anxiety.	Do not stay longer than necessary.
400 - 700	Immediate irritation in eyes, nose and respiratory organs. Even persons used to ammonia cannot remain in the vicinity.	Under normal circumstances no serious injuries during 1 hour.
1,700	Cough, cramp and serious irritation in nose, eyes and respiratory organs.	1/2 hour exposure can lead to serious injuries.
2,000 - 5,000	Cough, cramp and serious irritation in nose, eyes and respiratory organs	1/2 hour or shorter can lead to death.
7,000	Paralysed, suffocation	Lethal within a few minutes.

Notes

2 - 5ppm is detectable by smell and depends on the individual's health, the area temperature and the humidity. The advantage of the low perceptible concentration for ammonia is that it gives people an early warning, enabling them to get away immediately from a dangerous area. The fact that ammonia creates a mist in moist air can also be seen as a warning.

If a white cloud is created in a confined space, sight is restricted and the concentration is above 4% by volume, which can be below the lower flammability level.

6 Industrial refrigeration

6.1 Introduction

Industrial refrigeration covers a wide range of uses and operating conditions within the chemical, pharmaceutical and petrochemical industries, the oil and gas industry, the metallurgical industry, civil engineering, sports and leisure facilities, industrial ice making, and other miscellaneous uses. Food processing and cold storage, the beverage industry etc., which are normally considered a part of the industrial refrigeration sector, are presented in a separate section.

The present section is an updated version of the corresponding section of Technical Options Report from 1991 /TOR91/. New data has been obtained, among others, by enquiry among industrial refrigeration companies and organisations late 1993 /Hau93/.

6.2 Current situation

6.2.1 Types and volume of equipment

Industrial refrigeration systems are generally large, with a typical refrigeration effect of over 100 kW. The largest systems may produce several MW, and may contain tonnes of refrigerant. Typical system lifetime is 25-30 years.
Evaporation temperatures down to approximately -60^{o}C are generally achieved with one single refrigerant, while cascade systems using two different fluids are required for lower temperatures. However, most industrial equipment works at moderately low temperatures, say -20^{o}C and above.

Reciprocating compressors, screw compressors, and turbocompressors are used. While refrigerants can rather easily be changed in positive displacement compressors (recips, screws), a turbocompressor will normally have to be modified to work with a different fluid with the same temperature lift.

Industrial refrigeration systems are most often linked to a continuous (production) process, which makes system availability crucial, including a regular supply of refrigerant for service purposes. Technology based on new refrigerants and new system designs has to be well proven before it can be taken into use on a full scale.
The equipment is normally situated in industrial areas with no public access, often with operating personnel in constant attendance. Therefore, toxic or flammable refrigerants may be applied with a minimum additional cost. In some cases, the fluids being cooled are themselves toxic or flammable.
For these reasons, proven technology based on ammonia and hydrocarbons is obviously a viable choice for industrial refrigeration, provided that it is not hindered by national codes or regulations.

The volume of industrial refrigeration world-wide is not easily accessible. As a very rough estimate, 5000-8000 MW cooling capacity installed annually may be assumed. Historically, CFCs have accounted for 15-20%, while more than twice this amount has been with HCFC-22. Ammonia and hydrocarbons have covered the remaining, the latter to a rather limited extent of 5% in order of magnitude.

6.2.2 Refrigerants for industrial refrigeration

Refrigerants have to be chosen primarily according to the temperature level at which they are going to cool. A typical application pattern (until lately) is indicated in Table 6.1:

Table 6.1 Typical refrigerant application pattern in the past

Temperature region				
< -80°C	-80°C--45°C	> -45°C	>-30°C	> 0°C
Hydro-carbons (HC)	CFC-13 R-503 BFC-13 HC	Ammonia HCFC-22 R-502 HC	Ammonia HCFC-22 CFC-12 R-500 HC	Ammonia HCFC-22 CFC-12 R-500 CFC-11 HC

Liquid nitrogen is used for special purposes at cryogenic temperature levels. Only a small fraction of CFC consumption has been for temperatures below -45°C.

Hydrocarbons (methane, ethane, propylene, propane, (iso)butane etc.) cover the entire temperature range. They are used in the oil and gas industry and other industries handling flammable fluids, but not to any significant extent for other applications.

CFC-11 has been used in medium sized, low pressure centrifugal chillers. Positive pressure refrigerants applicable for temperatures above -45°C may be used in any type of refrigeration equipment.

Possible chemicals to replace CFC refrigerants were presented in the previous Technical Options Report /TOR91/. Some of the candidates were already in production at that time,

Table 6.2 Non-CFC refrigerant alternatives

Temperature region				
< -80°C	-80 - -45°C	> -45°C	>-30°C	> 0°C
Hydro-carbons (HC)	HFC-23 HFC-32* R-404A* R-407B* R-507* HC HCFC-22**	Ammonia HCFC-22 R-404A R-407A/B R-410A/R-507 HC HFC-134a**	Ammonia HCFC-22 HFC-134a R-404A R-407A/B R-410A/R-507 HC	Ammonia HCFC-22 HCFC-123 HFC-134a HC

* Above approximately -60°C

** HCFC-22 and HFC-134a are also being used in low temperature (multi-stage) centrifugal cycles

like HFC-134a, HCFC-123 and HFC-23. Since then, blends of HFCs (HFC-400 and HFC-500 series) have been composed to meet the requirements of replacing R-502 and, lately, also replacement candidates for HCFC-22. A summary of alternatives for different temperature levels is given in Table 6.2 (not exhaustive).
Field experience with HFC-134a is accumulating, both with respect to new systems and retrofits. Test results with HFC blends to replace R-502 have been published, and some field experience has been gained.

6.2.3 Refrigerant use. Trends and consumption figures

Last time the situation was evaluated by the Technical Options Committee (1990/91), annual use of CFCs for industrial refrigeration in developed countries (named "CFC market") was roughly estimated at 4500 tonnes/year /TOR91/. Out of this, 40 % (1800 tonnes) was estimated to be for new installations, while the remainder (60%, 2700 tonnes) was for service purposes. Corresponding figures for HCFCs (named "HCFC market") were 5000 tonnes/year for first charge and 7500 tonnes/year for replenishment. The designations "CFC market" and "HCFC market" will be retained in this report, pointing out application areas originally served by these groups of chemicals.

New system designs require less refrigerant charge. It is assumed that this will compensate for the forecasted capacity increase (3% per year, /TOR91/), keeping total refrigerant demand for new installations fairly constant.
Boundary conditions for the refrigeration industry have changed much since 1991. The dates for CFC phaseout have been moved forward, to January 1, 1996 world wide, and even one year earlier than 1996 in most European countries. Simultaneously, HCFC refrigerants, which were considered to be the main replacement fluids for the CFCs, have been included in the Montreal Protocol.

During 1991 - 1993, a considerable change in refrigerant consumption patterns has taken place. The use of CFCs in new installations has declined dramatically, and many companies have not installed new systems with CFCs at all in this period /Hau93/. In industrialised countries world wide, the use of CFCs in new installations in 1993 has most probably not exceeded 5-10% of the previous consumption level.
However, since the stock of existing systems is very considerable, a significant amount of CFCs will have to be available for service purposes for some years to come.
The European Union (EU) has proposed significantly stricter regulations on HCFCs than those prescribed by the Protocol, and HCFC use control affecting the industrial sector is currently under discussion. Several European countries are likely to ban the use of HCFCs in new systems around the year 2000.
For this reason, HCFC-22 is clearly losing ground as base fluid for the industrial sector in Europe. The situation may be similar in some other regions also, e.g. Australia/New Zealand.

However, accelerated HCFC phaseout has not been proposed in major industrial refrigeration markets like the United States and Japan. The outlook for different HCFC regulations makes a different development likely to occur. There is clear evidence that this is already the case.
In several European countries, industrial refrigeration companies have turned to ammonia first of all, which currently covers 70-80% of the market for new installations. In other parts of Europe, the trend is less pronounced, and average figures for the entire region may show a more even distribution between ammonia and HCFC-22.
So far, HFCs have gained 5-10% of the European industrial refrigeration market. Hydrocarbons are believed to account for 2-3%.

The development in the United States has been different. HCFCs remain to be the most attractive replacement fluids. Hydrocarbons would appear to be more commonly used than in Europe, while ammonia has shown only a modest growth rate. It is assumed that HCFCs will dominate the American industrial refrigeration market during the nineties, both for new systems and for retrofit purposes.

The consumption pattern in Japan is not very different from that in the USA. HCFCs dominates, although a growing use of HFC-134a is seen. While ammonia has been very uncommon in the past, a certain use of this refrigerant is expected for the future. Hydrocarbons are not applied as industrial refrigerants to any noteworthy degree in Japan.

Table 6.3 Estimated consumption of CFCs, HCFCs and HFCs. Industrialised countries 1993

Refrigerant type	Estimated consumption 1993, tonnes/year	Estimated "bank" of refrigerant, tonnes
CFCs	2600	30000
HCFCs	14000	80000
HFCs	400	800

Estimates for 1993 consumption of CFC, HCFC and HFC refrigerants in the industrialised world appear in Table 6.3. The table also includes estimates for refrigerant stocked in industrial refrigeration systems.

Compared to 1990/91, CFC consumption has been reduced by more than 40%. The remaining use is mainly for service purposes.

Since industrial refrigeration covers a variety of applications within different sectors of industry, and many systems are "tailor made" for their purpose, accurate estimates for consumption and "bank" are virtually impossible to achieve. The given figures can only indicate very rough orders of magnitude.

Transfer of technology to Article 5(1) countries under the Multilateral Fund is being organised by UN organisations (UNDP, UNEP, UNIDO) and the World Bank, as well as through bilateral programmes. The process is at an early stage, and it is not believed that it has significantly affected CFC consumption for industrial purposes in these countries so far.

Refrigerant consumption in Article 5(1) countries is expected to grow by 6% per year on average, in spite of lower charge per system. Current consumption figures are believed to be in the range of 500-1000 tonnes/year, both with respect to CFCs and HCFCs. HFC-134a has been introduced in some countries. So far, the consumption is believed to be insignificant.

6.3 Refrigerant conservation

The major portion of refrigerant consumption in the past has resulted from emission due to leakage and release during service and repair. While annual losses up to 30% of charge are not uncommon in some sectors, industrial systems are believed to show a much lower rate of 9%. Environmental regulations in an increasing number of countries, e.g. the Clean Air Act in the United States, include a ban on venting ozone depletion substances to the atmosphere. In some countries, like Sweden and the Netherlands, limits for maximum allowable leakage from refrigeration systems are introduced as well, and other countries may follow. It is believed, therefore, that emission figures will fall off considerably towards the end of the century. More leak proof designs and higher refrigerant prices will work in the same direction. The more stringent conservation practices will most probably be valid for HFC refrigerants as well. It is assumed that emission from industrial halocarbon systems will gradually reduce, to reach a lasting value of 6% of charge annually by the year 2000.

6.4 Existing equipment

6.4.1 General

According to Table 6.3, industrial refrigeration systems with 30,000 tonnes of CFC refrigerants are currently in operation. Remaining technical lifetime spans from zero to 25-30 years.

When new CFC refrigerants are no longer produced, existing systems will have to be operated on reclaimed or recycled fluid, if not retrofitted to use a non-regulated refrigerant, or taken out of service and replaced by a new system. Some CFC will certainly be stocked by end users, permitting undisturbed system operation for another 2-5 years or more. Stocking is particularly likely to occur with respect to systems with BFC-13, since retrofit to use another refrigerant cannot easily be done.

In Article 5(1) countries a 10 year period of grace applies, and CFCs may be used until 2006. However, many countries are aiming at a faster phaseout, and will adopt retrofit practices along with the development of proper procedures in industrialised countries.

6.4.2 CFC recovery and reuse

It will not be technically possible, nor economically justifiable to retrofit or take out of operation all industrial CFC systems within 1995 (Europe) or 1996 (world wide). Refrigerant recovery and reuse will play an important role in an interim period for CFCs and a continuing role for HCFCs and HFCs.

However, the regularity of (local) supply of high quality refrigerant for service purposes may be uncertain. It is believed, therefore, that many industrial end users will prefer to make themselves independent of CFCs as soon as practically possible.

By the year 2000, it is believed that one third of current CFC systems will still be in operation with their original type of refrigerant. During the subsequent five years, most of these systems will be taken out of service or retrofitted, leaving no installations with CFC left by 2010. It is assumed that 60% of stocked CFC, amounting to 18,000 - 20,000 tonnes, may be made available for reuse in the period 1995-2000. Even though this well exceeds estimated demand in the same period, according to a "most likely" scenario, shortages at the local level will most probably occur.

6.4.3 Premature decommissioning

Not all types of industrial systems can be retrofitted, e.g. low temperature systems with BFC-13. Moreover, retrofit technology and procedures in general are still not fully developed. Therefore, a significant number of systems may be retired rather than

retrofitted. Also, higher energy efficiency of modern systems and improved system flexibility through computerisation may motivate for complete system replacements.
Since system retrofit will primarily be applied to newer and medium-aged systems, premature decommissioning is assumed to become particularly significant during the first years without new CFCs. Among those systems which will be retrofitted or taken out of service prematurely before 2000, 20% are assumed to belong to the latter category.

6.4.4 Retrofitting

6.4.4.1 General

System retrofit means changing refrigerant with a very limited demand for technical modifications to the system. Experience has shown that refrigeration systems with CFCs may be retrofitted successfully to alternative, non-regulated fluids. In fact, the technical possibility of rather uncomplicated retrofits is the main reason why the very strong acceleration of CFC phaseout dates has been possible at all.

In retrofitting an existing system possible effects of remaining chemicals (refrigerant, oil, and break down products from these) must be taken into account, in addition to general material compatibility, and refrigeration properties like system pressure and cooling capacity. In principle, most systems can be retrofitted, either to an interim fluid containing HCFC or to an HFC alternative. Fluids containing HCFC will give the least change in system chemistry, since they contain chlorine and conventional lubricants can be used (alkylbenzene and, in some cases, mineral oil).
On the other hand, retrofit to a chlorine free refrigerant will be a permanent solution, and not affected by future HCFC regulations and possible shortages. Some European countries have proposed to ban HCFC use shortly after the year 2000, which, of course, makes interim fluids even less attractive for retrofit.
A modest 5-10% of companies' activities during the last three years has been in relation to retrofit /Hau93/. This figure is expected to increase dramatically.
It is assumed that 10% of the existing stock of CFC systems will have been retrofitted by the end of 1996, and that the bulk of retrofit work will be performed during 1997-99, covering one third of present stock by the year 2000. The remaining two thirds are assumed to be evenly divided between scrapping (naturally and prematurely) and operation on recycled or stockpiled CFC.

6.4.4.2 Replacements for CFC-12 and R-502

6.4.4.2.1 HCFC-22 and blends containing HCFC-22

HCFC-22 may in some cases be used for simple retrofit of systems with CFC-12 or R-502. In most cases, however, more extensive changes may be required due to much higher volumetric capacity compared to CFC-12 and higher discharge temperature compared to R-502. Nevertheless, HCFC-22 has been, and still is in many countries, a very attractive fluid for retrofit, since considerable experience exists at the engineer level.

Retrofitting to use HCFC containing blends, i.e. R-401A/B and R-409A to replace CFC-12 and R-500, and R-402A/B, R-403A/B and R-408A to replace R-502, may be simpler and less expensive.
The retrofit blends are zeotropes with a varying temperature glide. It is less than 2 K at the normal boiling point for the replacement fluids for R-502, which is considered to have no practical effect on system performance etc. Low glide also reduces possible problems related to fractionation.

The temperature glide of "drop-in" blends for CFC-12 (such as R-401A/B) is significant, however, (approximately 6 K) making retrofit more difficult. Problems which may arise are, among others, possible fractionation and increased pressure in shell and tube condensers, and reduced evaporator performance (particularly pool boiling). Great temperature glide will also make the mixtures less suitable for purposes requiring constant evaporation temperatures, for example ice making and the cooling of liquids close to the freezing point.

The differences between countries and regions with respect to HCFC regulations are naturally reflected in the preferences for system retrofit. In Europe 25% of future industrial retrofits are anticipated to involve HCFC-22 or blends with HCFC, while such alternatives are believed to be chosen three times as often in the USA/Japan.

6.4.4.2.2 HFC and HFC blends

Although being increasingly carried out in practice, HFC technology for system retrofit is still considered somewhat less mature compared to the installation technology of new HFC-134a systems (ref. Table 6.4 and 5). Reasons for this are, first of all, uncertainties in relation to possible effects of remaining chlorine and mineral oil, which in some cases may cause severe system failure (copper plating, excessive wear, blocking of throttling valves etc.) The situation, as judged by a number of European refrigeration companies, appears from Table 6.4.
It seems as if companies outside Europe consider more time necessary before fully developed HFC technologies for system retrofits will be at hand.

As stated, retrofit of CFC-12 systems to use HFC-134a has been performed to some extent already, and the technology is considered more or less mature for some applications, e.g. turbocompressor units. Retrofit procedures are still under development, and another 3-4 years or more may be required to have proper technology proven for all industrial application.

Table 6.4 Commercial maturity of HFC refrigerants for retrofit of industrial systems; Europe (scale 0-10; 0 - very early stage 10 - fully mature)

Refrigerant	Average score	Time until fully mature technology, years
HFC-134a	6.8	2 - 4
Other HFCs/HFC blends	4.7	3 - 5

Other HFCs than HFC-134a, including blends (ref. subsection 6.5.3.5), are at an even earlier stage in their development. So far, very few industrial systems (if any) have been retrofitted to an HFC other than HFC-134a. In principle, the problems should be similar to those with HFC-134a, and similar solutions should apply. Nevertheless, lack of practical experience gives a lower score (Table 6.4), and more time is expected to be required before safe retrofit procedures have been developed. HFCs are considered to be the most important retrofit option in Europe, and half of all retrofit activity is expected to involve HFCs. In the USA/Japan, the corresponding percentage is believed to be lower, and 20% is assumed.

6.4.4.2.3 Ammonia

Ammonia is normally not considered appropriate as a replacement for CFCs in existing equipment, due to lack of material compatibility (copper). This problem is less pronounced within industrial refrigeration, since steel is commonly used as construction material with all types of refrigerant. In some European countries, ammonia has gained a small percentage of the retrofit market, maybe 5% on average for the entire continent. In the USA/Japan retrofit to use ammonia is insignificant, and this fluid is not expected to play any role for future retrofits either.

6.4.4.2.4 Hydrocarbons

Hydrocarbons may be viable retrofit options in the oil and gas industry and some sectors of the chemical industry. A share of 5% of the world retrofit market may be assumed.

6.4.4.3 Replacements for CFC-11

HCFC-123 is the only fluid to replace CFC-11 in existing industrial chillers. The changeover is fairly straightforward with open type compressors, although seals, gaskets etc. have to be replaced. HCFC-123 is not compatible with the stator winding insulation material in semihermetic chillers, and retrofit may not be economically justifiable. Refrigerant recovery and reuse, combined with measures to reduce emissions, may prolong the working life of such chillers some years beyond CFC phaseout, before the units are replaced.

6.4.4.4 Replacements for CFC-13 and BFC-13

Changeover from CFC-13 to HFC-23 is rather simple, in principle, since the two fluids are very similar. However, ester oil must be used, and the requirement for system cleaning may be very strict due to low temperatures.
No single fluid may replace BFC-13 in existing systems. Reconstruction of the system to operate with HFC-23 and a higher temperature refrigerant in cascade may be possible, but costly. In most cases, however, early system retirement and a completely new installation is the most likely solution.

6.5 New equipment

6.5.1 Maturity of long term options

The enquiry revealed no outlook for a significant change in refrigeration technology in the near future. While absorption and adsorption refrigeration, evaporative cooling, gas cycles etc. have shown some progress, it is obvious that industrial refrigeration in general will be provided by the conventional compression cycle for still many years.

Ammonia technology has taken a considerable step forward, particularly in Europe, through the introduction of semihermetic ammonia compressors and soluble lubricants (polyglycols). New chillers with ultra low charge are emerging. Cooling capacities in the range of 15-25 kW per kg ammonia charge are common.
Another 5-10 years' development or more is believed to be required until alternative technologies may be competitive to any significant degree. A couple of per cent market share for not-in-kind technologies may be assumed by 2000. On the other hand, improved technologies for indirect cooling may reduce refrigerant demand. These include, among

others, pumpable ice slurry ("binary ice") for cooling and freezing purposes, and CO_2 used as a secondary refrigerant.

Table 6.5 *Commercial maturity of long term options; European refrigeration companies (Scale 0-10; 0 - very early stage 10 - fully mature)*

Refrigerant	Average score	Time until fully mature technology, years
HFC-134a	9.8	0 - 1
Other HFCs/HFC blends	5.7	2 - 3
Ammonia	7.1	1
Hydrocarbons	3.8	2 - 3
NIK-technology	2.7	5 - 10

Commercial maturity of various long term options, according to European refrigeration companies, is indicated in Table 6.5. According to the enquiry, the judgement with respect to maturation of HFC technology is slightly less optimistic outside Europe.

6.5.2 Refrigerants for the lower temperature region

Regulated low temperature fluids, CFC-13, R-503, and BFC-13, are already replaced in most new systems. HFC-23, which is very similar to CFC-13 and R-503 with respect to refrigerant properties, has taken over the market for the lowest temperatures. Low temperature hydrocarbons, e.g. ethane (normal boiling point -88.7°C), may be used also. Neither system costs nor efficiency are believed to have changed significantly.

There is no single refrigerant with properties similar to those of BFC-13. Application of the more volatile HFC-23, in combination with a higher boiling refrigerant in cascade systems, is believed to be the best alternative in most cases. Cascading results in increased system costs. On the other hand, the lower temperatures available with HFC-23 may yield economic benefits, for example with respect to optimal product yield in condensation of industrial gases (SO_2, Cl_2 etc.). HFC-32 (flammable) and HFC blends designed for replacement of R-502 in low temperature equipment may cover parts of the upper temperature region of BFC-13.

6.5.3 Refrigerants for the medium and upper temperature regions

6.5.3.1 Ammonia

As pointed out in the previous Technical Options Report /TOR91/ see also section 5, ammonia has many advantages as a refrigerant, both from a technical point of view and with respect to environmental effects. Regulations and subsequent phasing out of HCFCs have increased its importance even more. Ammonia should always be considered when selecting refrigerants for installations in the industrial sector. Even though it has been on stage for more than 100 years, ammonia did not get a top score in Table 6.5 with respect to technical maturity. This may reflect a potential for further technical improvements in general, as well as some uncertainty with respect to the "new" ammonia technology (ref. subsection 6.2.2). However, the time until full maturity is considered to be very short.

Strict legal restrictions on the use of ammonia and historically low interest in this refrigerant have made ammonia systems very uncommon in some countries and regions, e.g. Japan. A trend towards a more general acceptance of this refrigerant is apparently developing, however.

The new ammonia technology will probably not affect that part of the industrial market which depends on tailor made systems to any great extent. It is believed, however, that more standardisation will also take place within the industrial sector. Chillers, which are already extensively used, will most probably become even more common in the future. Since the new technology is particularly aimed at chillers, it will certainly become of great importance to industrial refrigeration. As stated already, ammonia has taken over a considerable part of the "CFC-market" in Europe. A further growth is to be expected, but probably less pronounced when new HFC blends enter the market. By 2000, it is believed that 40-50% of applications previously covered by CFCs will be served by ammonia systems in Europe. A very similar trend is also seen with respect to the European "HCFC market". Ammonia is replacing HCFC-22 in new systems to a considerable extent, and a similar market share to that indicated for the "CFC market" may be expected by 2000. For reasons discussed already, the development in the United States and Japan may show a different pattern. However, ammonia is expected to gain shares of these markets also, but only with moderate figures of 10-15% by 2000.

Ammonia is commonly used in many Article 5(1) countries, due to simple technology, high system reliability and good availability and low cost of the refrigerant. Future development is believed not to be very different from that in industrialised countries. The use of ammonia may expand significantly in those countries where it is common today, while the introduction into new markets may be more slow. For the reasons stated above, Article 5(1) countries should be encouraged to expand their use of ammonia.

Somewhat improved cycle efficiency with ammonia may compensate for efficiency loss caused by the more extensive use of indirect systems. No net effect on energy consumption is expected, therefore. System costs are expected to change -10% to +50%, dependent on application. The new series of low charge ammonia chillers have significantly reduced the cost difference with respect to this application area. On average, a 5-10% increase may be indicated. More detailed information about ammonia applications and properties can be found in section 5.

6.5.3.2 HCFC-22

From a technical point of view, HCFC-22 may rather easily replace CFC-12 (and also R-500/502) in most new systems. However, future regulations and eventual phaseout have made this solution less attractive.

As previously stated, installation of HCFC-22 systems is declining very fast in those parts of Europe where ammonia is commonly used. Moreover, HFC blends have been identified, which may replace HCFC-22 without sacrificing any thing with respect to cost and efficiency. Availability is very limited so far and the technology is still under development (Table 6.5). The situation may look different in a couple of years. HCFC-22 is anticipated to cover 10-20% of the CFC market in Europe by 1996, while it still may hold half of its own traditional market. It is assumed that by 2000, HCFC-22 consumption for new systems will be very low in general, most probably less than 10% of the previous level. In the United States and Japan, HCFC-22 is by far the most important CFC replacement refrigerant for industrial purposes today (90% of the total). HCFC-22 will most probably dominate for quite some time to come, even though HFC refrigerants and ammonia will gradually penetrate the market. In these regions HCFC-22 is expected to cover 2/3 of the "CFC market" in 1996 and half of it in 2000. For typical HCFC-22 applications, 85% (1996) and 60% (2000) HCFC use is assumed. The cost effect of replacing CFC-12, R-500, and R-502 by HCFC-22 is not believed to be substantial, maybe 5% up on average, due to more frequent use of two stage systems. For the same reason, a minor (5%) reduction in energy consumption can be expected.

6.5.3.3 Refrigerant blends with HCFCs

Refrigerant blends with HCFC-22 as the main component have been developed, mainly for retrofit purposes, e.g. R-401A/B, R-402A/B and R-403A/B. It is not believed that these blends play, or will play, any significant role as refrigerants for new industrial systems.

6.5.3.4 HFC-134a

HFC-134a technology is considered to be nearly mature for new systems (Table 6.5), and it has gained a certain share of the industrial market. Technically, it is a logical replacement for CFC-12, not least in turbocompressor units. One reason for a rather modest growth is its lower refrigeration capacity and corresponding demand for larger compressor volumes compared to ammonia, HCFC-22 and the high pressure HFC blends. It is assumed that HFC-134a will cover 10% of the "CFC market" world wide by 1996 and 5% of the "HCFC market". These percentages are not expected to change significantly thereafter.

Above -10°C evaporation temperature, cooling capacity and system efficiency are not substantially less with HFC-134a than with CFC-12. At lower temperatures, up to 15% increase in energy consumption and 30% loss in capacity may result. Even though the difference may be compensated for by extensive liquid subcooling or two stage arrangement, higher pressure fluids are believed to be preferred at these temperatures.

Initial cost for HFC-134a systems is approximately 10% higher compared to former CFC-12 systems.

6.5.3.5 HFC blends

HFC blends designed to replace R-502 contain HFC-125, HFC-143a, and HFC-134a, like R-404A, or with HFC-143a replaced by HFC-32, like R-407A. In addition an azeotropic mixture of HFC-125 and HFC-143a (R-507) is available. Development of HFC blends to replace HCFC-22 is on the way. The most promising candidates so far are a three component mixture of HFC-32, HFC-125 and HFC-134a (R-407C), and an azeotrope between HFC-32 and HFC-125 (R-410A). Both alternatives show somewhat lower efficiency than HCFC-22 in non-optimised equipment, the difference being largest for the azeotrope (10-20%) /Tec93/.

While the flammable HFC-32 may be applied as a single refrigerant for some purposes (favourable with respect to global warming potential), it is believed that the major use of HFC fluids for R-502 or HCFC-22 replacements will be non-flammable blends. Some of these mixtures, including the one intended for HCFC-22 replacement, are with significant temperature glide. HFC blends for the replacement of R-502 are available in limited quantities, and have been taken into use to a certain extent. This particularly holds for R-404A in low temperature, one stage systems. HFC blend technology is not yet considered fully mature (Table 6.5). Practical tests are being performed, however, and industrial systems may be ready for the market in less than 3 years. Refrigerant production capacity may be a limiting factor with respect to volume in the short term.

Even though zeotropic mixtures (of hydrocarbons) have been used within the oil and gas industry for years, other sectors have previously shown little interest in this option. This may change in the future, and it is believed that present objections against refrigerants with temperature glide will decrease along with practical experience gained with such fluids. However, these mixtures will be less suitable in shell and tube evaporators and condensers with the refrigerant on the shell side, and in recirculation type refrigeration systems. Significant temperature glide will impose some cost effects, since evaporators and condensers have to be redesigned to fit this particular refrigerant property. More expensive refrigerant and ester lubricant will add to the total. 10-20% increase in initial cost may be indicated as a rough estimate. For azeotropes or fluids with a very low glide, the difference may be less. Optimised systems will most probably be similarly efficient to present systems with R-502 and HCFC-22 respectively.

Anticipated future demand for HFC blends corresponds to 10% of both CFC and HCFC markets by 1996. By the year 2000, 20% (CFC market) and 25% (HCFC market) will apply.

6.5.3.6 Hydrocarbons

Hydrocarbons are long term, proven refrigerants, which may fit into any temperature range, and their thermodynamic properties are excellent. In spite of this, and the fact that they are cheaper than the corresponding halocarbons, the latter chemicals have been used mostly within industries handling flammables. This situation has changed to some extent, as reported in the previous Technical Options Report /TOR91/. However, the development has apparently gone rather slowly up to now. A somewhat faster changeover is expected in the future, and hydrocarbons may take over portions of the market within the oil and gas industry and the petrochemical industry. Within other sectors, any significant changeover to hydrocarbons seems unlikely.

Estimates for hydrocarbon use are 5% and 8% of the "CFC market" by 1996 and 2000 respectively. Corresponding figures related to the "HCFC market" are insignificant consumption (1996) and 8% (2000).

6.5.4 Refrigerants for the upper temperature region

HCFC-123 may replace CFC-11 in low pressure industrial chillers in the short and mid-term perspective, and new units with this fluid have been on the market for some time. Only a few HCFC-123 chillers have been installed in Europe so far, and the future market is believed to be nearly non-existent due to the accelerated HCFC phaseout. The situation is different in the USA and Japan, where HCFC-123 is replacing CFC-11 to a certain degree. However, a big portion of the chiller market has moved to positive pressure units with reciprocating or screw compressors. A low AEL value of 30 ppm has worked against its use.

HFC-245, which may be an alternative to HCFC-123 in chillers, is currently still at the discussion level, and it is uncertain whether it will ever be manufactured. System efficiency with HCFC-123 is comparable or better to that of CFC-11. Cost is estimated 10% higher compared to CFC-11. Future demand for HCFC-123 is not expected to be very significant, and is in the present analysis assumed to be included in the figures given for HCFC-22. The same assumption holds for HCFC-124, which also may be taken into use, but most probably not to any significant extent.

6.6 Future development in Article 5(1) countries

In principle, appropriate refrigeration technology for developing countries will be similar to that of the industrialised world. Many industries in these countries are engineered or owned by companies in the developed world, and the policy of the parent companies will have great impact on the development, also with respect to refrigeration and refrigerants. Therefore, future development in many Article 5(1) countries will most probably show a similar pattern to that in the developed countries. Big countries, like China and India, may develop more independently.

Due to depressed economy and less technical competence in many countries it is of greatest importance that final, long term solutions are properly tested before the technology is transferred. Local expertise can most effectively disseminate new technology, and the education and training of local engineers and technicians should be given high priority.

6.7 HCFC requirements

Since 1991 the situation regarding HCFC requirements in CFC phaseout has changed, particularly with respect to new systems. Technology with HFC-134a and ester lubricant is nearly fully developed. Even though much less experience is available with the other HFCs, similarity to HFC-134a makes it reasonable to believe that HFC blends with negligible glide can be implemented without many problems. Experience so far supports this assumption.

Due to limited production capacity, shortage of refrigerants for temperatures typical for R-502, such as HFC-404A and HFC-407A/B, would result if HCFC-22 was no longer available. It is believed that the supply of low temperature HFC blends will be sufficient to cover market needs in 5-10 years.

HCFC-123 chillers may be advantageous with respect to energy efficiency and cost. Technically, the demand can be met by any refrigerant, using positive displacement compressors. Moreover, centrifugal chillers with HFC-134a are moving downwards in capacity, covering the upper part of the former capacity range of CFC-11.

HCFCs will be particularly important in connection with retrofit. During the first couple of years, neither the technology nor supply of HFC alternatives will be available to cover CFC retrofit demands. Furthermore, it is very questionable whether many older systems (more than 10-15 years) should be retrofitted to an HFC alternative at all, due to the strong change in internal system chemistry.

Some HFC blends to replace HCFC-22 have been identified, and are currently under practical evaluation. However, they are not expected to be on the market in significant quantities until the end of the decade. After 2005, the supply of alternative fluids may be sufficient to enable industrial refrigeration to cope completely without HCFCs for new systems. This particularly holds for the industrialised world, while Article 5(1) countries may require HCFCs for another 5-10 years.

There are many open questions in relation to the possible retrofit of HCFC-22 systems. The most promising HFC candidate has a very significant glide of 7 K, which may affect system performance, as previously described. Until these questions are fully clarified, and through a considerable period of time required to build up refrigerant production capacity and perform the retrofit work, HCFC-22 must be available for service purposes.

Similar arguments may be used with respect to the replacement of HCFC-123 in low pressure chillers. In this case, availability of a possible fluid for retrofit is even further into the future.

6.8 Forecast of use

Future refrigerant demand is forecasted using a "best guess" scenario presented in the foregoing text. It is assumed that 1/3 of the market world wide will develop according to the "European model", including accelerated HCFC phaseout and a significant change-over to ammonia, while 2/3 will follow the USA/Japan. Results regarding industrialised countries are summarised in Table 6.6. CFC demand is gradually declining, and it is believed that it will reach zero before 2010. Since no new product will be available after 1994 (1995), the supply will have to be based on reuse and virgin CFC stocked by end users. HCFC consumption is not expected to change much during the first 3-4 years, even though considerable amounts of fluid will be used to retrofit CFC systems. The reason is an anticipated transfer from HCFC to HFC and ammonia in new systems, and reduced emissions. Towards the end of the decade, with less retrofit activities and HFC alternatives to HCFC-22 available in significant quantities, reduction in HCFC demand is likely to accelerate.

Table 6.6 *Forecast of refrigerant demand; developed countries*

Year	Type of halocarbon			
	CFC	HCFC	HFC	Sum
1994	2500	13200	800	16500
1995	2300	12900	1200	16400
1996	1900	12900	2000	16800
1997	1500	12500	2800	16800
1998	1100	11700	3600	16400
1999	700	10300	3400	14400
2000	500	8900	3100	12500
2005	100	6000	5000	11100

HFC demand is believed to increase sharply to a level of more than 3000 tonnes/year in connection with CFC system retrofit. When HFC alternatives to HCFCs are expected to be mature towards the end of the decade, another very significant increase in HFC consumption is foreseen. Total halocarbon consumption is expected to fall off, however, due to more extensive use of ammonia and hydrocarbons, more leak proof systems, and world wide ban on venting environmentally harmful refrigerants. Taking recovery and possible reuse into account, reduction in demand for new chemicals may be even more pronounced.

The potential for CFC recovery in connection with system retrofit and retirement, as given by the scenario, is indicated in Table 6.7. Similar figures for HCFC-22 are also included. In practice, only a fraction of the potential for recovery can be utilised as refrigerant. The charge at system decommissioning may be less than the nominal amount, some fluid may be vented illegally, some refrigerant may be too heavily contaminated for reuse and so on. Therefore, a "recovery efficiency" of 60% is introduced, to estimate average practical yield of useful fluid. According to the analysis, CFCs available from retrofits and retired systems exceed the estimated demand, even with a relatively low "recovery efficiency" of 60%. However, local shortage may occur. The volume of retrofit and premature system scrapping, which is built into the scenario, can be illustrated by the fact that it implies retrofit or extraordinary replacement of 1.4 existing systems for each new system installed in the "CFC-market" on average 1995-2000. At maximum (assumed to be 1998), 2 retrofits/additional replacements per new unit apply. Work related to retrofit and early system retirement may represent an average increase in companies' activity level in the order of 15-25%, taking into account that most activities are related to the "HCFC-market", and, in Europe particularly, the "ammonia-market". This increase could be possible to manage, provided that no unforeseen technical problems related to retrofit appear. Good planning and organising of the work will be required. It seems very likely, however, that shortage of service engineers will occur from time to time.

Table 6.7 *Potential for CFC and HCFC recovery*

Year	Amount CFC, tonnes		Amount HCFC, tonnes	
	Potential	Available for reuse (60%)	Potential	Available for reuse (60%)
1994	1600	960	3400	2040
1995	2400	1440	3400	2040
1996	3500	2100	3500	2100
1997	4300	2580	3600	2160
1998	4700	2820	3600	2160
1999	3500	2100	3700	2220
2000	2000	1200	3800	2280
2005	1000	600	4200	2520

CFC consumption in Article 5(1) countries, estimated at some 500-1000 tonnes per year, is expected to keep at the current level for some years to come, but most probably fall gradually off after 2000. HCFC-22, with a similar estimated consumption as CFCs by 1993, is expected to cover the major portion of an assumed 6% annual market increase in the short and mid-term in the developing countries. Corresponding estimates for annual HCFC consumption amount to around 1000 by 1995 and 1200-1500 tonnes by 2000.

While only a minor HFC consumption is assumed for Article 5(1) countries by 1996, 100-200 tonnes per year may be assumed by the end of the decade.

References

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7 Air conditioning and heat pumps (air-cooled systems)

7.1 Introduction

On a global basis, air-cooled air conditioners and heat pumps (generally defined as "reversible heat pumps") ranging in size from 2.0 kW to 420 kW comprise a vast majority of the air conditioning market. In the remainder of this section the term air conditioning will be used to apply to both air conditioners and heat pumps. This broad category often is referred to as unitary equipment. These systems cool, dehumidify and/or heat everything from single rooms to large exhibition halls. Essentially, all are electrically driven vapour-compression systems using hermetic rotary, reciprocating or scroll compressors for units with capacities up to about 100 kW, and single or multiple semi-hermetic reciprocating or screw compressors for units with capacities up to 420 kW. Nearly all of these units use HCFC-22 as their working fluid. Air in the space to be cooled, or dehumidified, is drawn over a coil containing evaporating refrigerant. The air gives up the heat it contains to the circulating refrigerant. In heat pumps, the refrigerant circulation is reversible. In the heating mode, air from the conditioned space passes over the same coil that now contains gaseous refrigerant in the process of condensing to a liquid. In the process, the condensing gas transfers heat to the air. An estimated 1,450 GW capacity of air conditioners and heat pumps is installed world-wide.

Considering the diversity of loads and that some equipment will be idle at any given moment, unitary equipment accounts for an estimated 55,000 MW average power demand. Refrigerant charge quantities vary proportional to capacity. Assuming an average charge of 0.25 kg per kW of capacity, those 1,450 million kW of installed capacity represent approximately 364,000 metric-tonnes (1000 kg) of HCFC-22.

7.2 Current use

Air-cooled air conditioners and heat pumps generally fall into four distinct categories, based primarily on capacity: room air conditioners; duct-free packaged and split systems; ducted systems; and single packaged units or split systems intended primarily for commercial use (commercial unitary). Estimates of the installed base (number of units) and refrigerant inventory have been made, /Cha93/, /Kel93/.

7.2.1 Room and packaged terminal air conditioners

On a world-wide basis, an estimated 7.4 million room and packaged terminal air conditioners were sold in 1993; each one containing an average of 0.64 kg of HCFC-22. With service lives of 10 to 15 years, it is estimated that more than 65 million room and packaged terminal air conditioners remain in operation.

Because of their size and relatively low cost, room air conditioners (used in small shops and offices as well as apartments and other residences) are often the first mechanical refrigeration individual comfort cooling products to appear in developing nations (evaporative air-coolers often precede mechanical refrigeration in areas having low outdoor humidities).

Room air conditioners can be mounted in a window, through a wall, or even rolled from room to room. Room air conditioners range in capacity from less than 2.0 kW up to 10.5 kW. All use hermetic rotary, reciprocating or scroll compressors. The total world-wide inventory of HCFC-22 in room and packaged terminal air conditioners is estimated to be 42,000 metric-tonnes.

7.2.2 Duct-free packaged and split systems

In many parts of the world, the greatest demand is for the duct-free split system. Duct-free split systems include a compressor/heat exchanger unit installed outside the space to be cooled or heated. The outdoor unit is connected via refrigerant piping to one or more fan coils inside the conditioned space. There is generally one fan coil unit for each conditioned room. Small duct-free split systems with a single indoor fan coil often are categorised as **split room air conditioners.**

Duct-free split systems can be applied to commercial buildings, schools, apartments and free-standing residences. An estimated 80 million ductfree units are installed world-wide. Duct-free split systems, ranging in capacity from 2.0 kW to 20 kW, have gained greatest acceptance outside of North America due to different construction methods and a preponderance of hydronic or non-central heating systems. Smaller capacity duct-free split systems use hermetic rotary compressors while larger models use hermetic scroll or reciprocating compressors. Duct-free split systems having average HCFC-22 charge levels of 0.32 to 0.34 kg per kilowatt /Mor93/ of cooling capacity.

The total inventory of HCFC-22 in duct-free split systems world-wide is estimated at 101,000 metric-tonnes.

7.2.3 Ducted residential unitary systems

These systems dominate the North American market where central, forced-air heating systems necessitate the installation of a duct system that supply air to each room of a residence or small zones within commercial or institutional buildings. A compressor/heat exchanger unit outside the space to be cooled or heated supplies refrigerant to a single indoor coil installed within the duct system. Air that is cooled or heated by passing over the coil is distributed throughout the building.

An estimated 59 million ducted split systems are currently in service world-wide - the majority within North America. Capacities range from 5 kW to 17.5 kW and each has an average HCFC-22 charge of 0.26 kg per kilowatt of capacity. The total estimated inventory of HCFC-22 in ducted systems (< 17.5 kW) is 168,000 metric-tonnes.

7.2.4 Ducted commercial unitary systems

Many of these single packaged air conditioners and heat pumps are mounted on the roof of individual offices, shops or restaurants or outside the structure on the ground. Multiple units containing one or more compressors are often used to cool entire low-rise shopping centres, schools, hospitals, exhibition halls or other large commercial structures. Other commercial unitary products include indoor packaged units as well as split systems with an outdoor compressor heat exchanger unit connected by refrigerant piping to one or more indoor fan coils over which air passes to be cooled or heated.

An estimated 10 million commercial unitary air conditioners and heat pumps are installed world-wide. They range in capacity from about 20 kW to as much as 420 kW. Commercial unitary equipment carries an average HCFC-22 charge of about 0.31 kg per kilowatt of capacity. The estimated total world-wide inventory of HCFC-22 in these systems is 53,000 metric-tonnes. This estimate does not include commercial water chillers which are covered in section 8 of this report.

7.2.5 Summary of unit population and refrigerant inventory

The common attribute of these four equipment categories is their use of HCFC-22 as a working fluid. On a world-wide basis, HCFC-22 accounts for nearly all of the refrigerant fluids used in these product categories. HCFC-22's higher density and thermal efficiency have resulted in highly cost-effective products when compared to non-vapour compression cycles or products using lower pressure refrigerants. The following table summarises the total estimated inventory of HCFC-22 used in these product categories.

Table 7.1 ***Estimated unit population and HCFC-22 inventories for various unitary product categories***

Product Category	Estimated Unit Population (1994)	Estimated HCFC-22 Inventory (metric-tonnes)
Room and Packaged Terminal Air Conditioners	**65 million**	**42,000**
Duct-free Packaged and Split Systems	**80 million**	**101,000**
Ducted Split Systems	**59 million**	**168,000**
Commercial Unitary Systems	**10 million**	**53,000**
Total	**214 million**	**364,000**

7.3 Alternative refrigerants and cycles

Two areas must be considered in any discussion of new products that do not use HCFC-22 as a working fluid: alternative refrigerants and non-vapour-compression cycles. In either case, the future environmental impact of these new technologies must be carefully considered.

Today, refrigerants have been targeted as greenhouse gases due to their relatively high direct global warming potentials (GWP). However, a more indicative measure of the effect of any technology on global warming is its Total Equivalent Warming Impact, TEWI. TEWI combines the (direct) effect due to the release of refrigerant into the atmosphere as well as the (indirect) effect of the CO_2 produced in generating the energy necessary to run the equipment. For unitary equipment, the indirect effect can represent over 90 percent of the Total Equivalent Warming Impact. It is therefore important that both the direct and indirect global warming impact of alternative refrigerants be considered. The important point evidenced from a TEWI analysis of the unitary equipment options is that the energy efficiency of the unit is very important. Table 7.2 shows how the TEWI changes as a function of direct GWP and Seasonal Cooling COP for units installed in Pittsburgh, PA. These calculations were done for a 3.5 kW base model unitary air conditioner with an assumed 5% annual make-up rate /ALS/. The calculations were consistent with the AFEAS /Fis93i/ report on alternative technologies. The table demonstrates that the direct GWP of the refrigerant is less important than the efficiency of the unitary system. Therefore, a refrigerant or refrigerant blend should not be excluded from possible future development simply because it has a GWP greater than zero. Conversely, technologies which utilise working fluids with low direct GWP should not be favoured unless they also result in less total energy use /TEW/ and thus low TEWI.

Table 7.2 *Total Equivalent Warming Impact as a function of GWP and seasonal cooling efficiency (kg-CO_2/year)*

GWP	Seasonal Cooling Coefficient of Performance					
	2.9		3.2		3.5	
	Indirect	Total	Indirect	Total	Indirect	Total
0.0	806.6	806.6	733.3	733.3	672.2	672.2
47.6	806.64	854.3	733.3	780.9	672.2	719.8
95.3	806.6	901.9	733.3	828.6	672.2	767.5

1. GWP is based on CFC-11, and 100 year ITH (3500 kg CO2/kg-CFC-11)
2. Leak Rate assumed to be 5 Percent per year
3. Refrigerant quantity assumed to be 0.25 kg per kW
4. Power plant contribution of 0.672 kg-CO2 /kW-hr (North American average /FIS93ii/)
5. 1000 cooling load hours per year (Pittsburgh, PA USA)

In the following sections, the predominant HCFC-22 alternative refrigerant and cycle technology options will be presented. These choices are currently being evaluated by refrigerant and HVAC manufacturers as potential HCFC-22 system replacements.

7.3.1 Alternative refrigerants

As discussed above, HCFC-22 is used almost exclusively as the working fluid in air-cooled vapour-compression air-conditioners and heat pumps. The Montreal Protocol calls for all HCFCs to be phased out by the year 2020 with a small "service tail" allowed until 2030. Therefore, refrigerant and equipment manufacturers world-wide are actively researching zero-ODP refrigerants to replace HCFC-22 in these product categories. Section 2 of this report provides technical data for each of the refrigerant options discussed in this section.

7.3.1.1 AREP

The ARI HCFC-22 Alternative Refrigerants Evaluation Program, AREP, is one effort by which the international community is co-operating to evaluate HCFC-22 replacement candidates. Participants in the program include equipment manufacturers and researchers from the United States, Canada, Japan, and Europe. In an attempt to identify promising zero-ODP replacements for HCFC-22, these companies have agreed to test candidate refrigerants at their own expense and to make the results publicly available. The scope of AREP is to fairly and uniformly evaluate the performance of equipment with the various

Table 7.3 ***Refrigerants and refrigerant blends tested as HCFC-22 alternatives in ARI's HCFC-22 Alternative Refrigerants Evaluation Program***

Refrigerant or Refrigerant Blend	Percent Composition[2] (by weight)
HFC-134a ‡	100
HC-290 (propane) ‡	100
R-717 (ammonia)	100
HFC-32/125 †	50/50[3]
HFC-32/125 ‡	60/40[4]
HFC-32/134a ‡	20/80
HFC-32/134a ‡	25/75
HFC-32/134a ‡	30/70
HFC-32/134a	40/60
HFC-23/32/134a	1.5/20/78.5
HFC-23/32/134a	1.5/ 27/71.5
HFC-23/32/134a	2/29.4/68.6
HFC-125/143a	45/55
HFC-32/125/134a †	10/70/20
HFC-32/125/134a †	23/25/52[3]
HFC-32/125/134a	24/16/60
HFC-32/125/134a	25/20/55
HFC-32/125/134a ‡	30/10/60
HFC-32/125/134a/HC-290	20/55/20/5

Notes:

1. Refrigerants are not listed in any particular ranking order.
2. Compositions are nominal, and do not include deviations of charged or circulating compositions from nominal.
3. This refrigerant has been recently proposed as an alternative composition of a previously-tested blend. Manufacturers may choose to pursue this alternate composition in lieu of the other composition.
4. Some refrigerant producers have recently suggested an alternate composition of this blend.

‡ Discussed in following sections

† Formulation submitted for ASHRAE refrigerant number and safety classification

prospective refrigerants. It is not intended to pick a single or even a group of refrigerants to replace HCFC-22. Furthermore, AREP does not address such important issues as flammability, toxicity, etc. Other programs are underway to look at these topics (Section 14.5). Table 7.3 lists the candidate refrigerants that have been tested under the AREP program. These fluids include pure refrigerants and blends (ranging from azeotropes to zeotropes that exhibit glides of about 5 K). Although the AREP effort has tried to concentrate on the most promising refrigerants, this list does not represent every possible HCFC-22 alternative. Longer range efforts to develop alternative refrigerants are discussed in sections 7.3.1.2. The most promising candidates currently identified are discussed in section 7.3.1.3. The original AREP testing effort is essentially complete. The preliminary conclusion, based on compressor calorimeter, system drop-in and soft-optimisation test results, is that there may be several viable alternatives that might perform similar to, and with appreciable system redesign possibly better than, HCFC-22 in terms of capacity and/or efficiency. However, there is no single refrigerant that outperforms all other alternatives in the various types of equipment tested. In fact, the marketplace may support several alternative refrigerants, and the choice of a refrigerant may vary by application and/or system design.

Full optimisation of equipment will not be performed under AREP. It remains to be seen how future zero-ODP products will compare to today's HCFC-22 equipment in terms of efficiency, safety, cost and reliability.

7.3.1.2 Other work/results

In addition to the AREP program equipment manufacturers, chemical companies, universities and other research organisations around the world are conducting extensive research programs aimed at locating suitable replacements for HCFC-22. The results of some of this work has been published in technical journals and conference transactions; however the results of much of this research has not been published. The Air-Conditioning and Refrigeration Technology Institute, (ARTI) Refrigerant Database /ART/ consolidates and facilitates access to much of the published information. Additional sources of information can be located in section 14 of this report.

7.3.1.3 Primary replacement candidates

The preliminary results of the AREP program indicate that in addition to the single-component refrigerants such as HFC-134a, HC-290 and R-717 several of the refrigerant blends show significant potential as HCFC-22 replacements. There may also be alternatives which were not tested under the AREP program. These results offer considerable optimism that a suitable replacement for HCFC-22 can be found within the time frame dictated by the Montreal Protocol.

Following is a brief summary of some of the candidate refrigerants being considered for air-cooled systems. It should be noted that the industry is only in the early stages of finding HCFC-22 originally alternatives. For instance, the results summarised below are from tests with compressors designed for HCFC-22. As such, those results do not necessarily represent the anticipated performance in fully optimised equipment. Much work is still needed before systems using zero-ODP refrigerants can be produced on a large scale.

7.3.1.3.1 HFC-134a

Under the AREP, pure HFC-134a is being examined mainly as a replacement for HCFC-22 in large chillers. This equipment category is addressed in section 8. However, HFC-134a should not be ruled out as a potential replacement for HCFC-22 in unitary equipment. There are, however, some significant hurdles to be overcome before such a changeover is feasible.

HFC-134a cannot be considered a *drop-in* replacement for HCFC-22 in unitary equipment. With HFC-134a, systems designed for HCFC-22 are about five percent less efficient and have 40 percent less capacity under typical unitary equipment operating conditions with HCFC-22. It is possible to design unitary equipment using HFC-134a that will have the same system efficiency and capacity as HCFC-22, but only up to a point. Significant equipment redesigns are necessary to achieve equivalent efficiency and capacity. Those redesigns include enlarged heat exchangers and refrigerant tubing, larger volumetric displacement compressors, and re-sized compressor motors. Many of these changes will require significant capital investment.

However, as the cooling efficiency targets increase, they become more and more difficult and costly to achieve with HFC-134a. For cooling, with COPs of approximately 4.0 equipment may be 30 to 40 percent more costly to build. As the cooling efficiency targets are raised even higher, which is likely to occur, HFC-134a designs may become impractical. In the heating mode, system heating efficiencies are impacted more significantly than the cooling efficiencies. This may limit the practicality of HFC-134a heat pumps.

7.3.1.3.2 HFC-32/125

A 60/40 (weight percentage) composition of this mixture was initially investigated under AREP. Compressor calorimeter results have shown an increase in compressor capacity on the order of 40 to 50%, but a decrease in efficiency up to 10%. System tests with soft-optimised systems have shown comparable or greater performance than HCFC-22. These system efficiency gains have been attributed to the favourable thermophysical properties of this refrigerant. A negative attribute of this refrigerant is its high operating pressure. System pressures with this blend are approximately 50 percent higher than with HCFC-22. System designers will have to address the higher operating pressures through design changes. Different compositions of this mixture are also under investigation as a result of concerns over flammability of the 60/40 composition. A 50/50 composition was submitted for ASHRAE 34 number designation and safety classification (R-410A).

7.3.1.3.3 HFC-32/125/134a

A 30/10/60 composition of this mixture was initially investigated under AREP. Compressor calorimeter results have shown capacities and efficiencies within ±10% of HCFC-22, using HCFC-22 compressors. This blend shows promise as an acceptable OEM and retrofit refrigerant. Flammability concerns may also require a change in the composition of this blend. A 23/25/52 weight percentage composition of this blend was submitted for ASHRAE 34 number designation and safety classification (R-407C).

7.3.1.3.4 HFC-32/134a

A 30/70 composition of this mixture was initially investigated under AREP. Compressor test results have shown capacities and efficiencies close to those of HCFC-22. Flammability concerns caused some manufacturers to test both a 25/75 and 20/80 weight composition of this mixture. These blends have exhibited lower performance than the 30/70 composition.

7.3.1.3.5 HC-290 and other hydrocarbons

Either HC-600a or HC-290/HC-600a blends are being used in domestic refrigeration appliances in Europe (see sections 3.7.2.2 and 3.4.2.2). These systems have refrigerant charge levels of approximately 30 grams. The market potential of HC technology in domestic refrigeration in Europe is considered high. Very little has been reported on the use of HC refrigerants in unitary products. One US unitary equipment manufacturer has developed a prototype packaged air conditioner using HC-290. This manufacturer reported /ARI94/ that the use of HC-290 in this product would increase the cost by 30 percent if product improvements suggested by Underwriters Laboratory were to be incorporated into the design.

Only limited data on HC-290 (propane) pure refrigerant are available from the AREP program. The compressor calorimeter results indicated that capacities with propane are lower than HCFC-22 (although this can be compensated for by increasing compressor displacement), and efficiencies are similar to HCFC-22. The use of hydrocarbons in unitary products that have much higher charge levels (0.25 kg per kilowatt of cooling capacity) is the subject of considerable debate in the HVAC community. The principle concern is product safety. A recent workshop /ARI94/ has expanded the industry dialogue on the use of flammable refrigerants. The primary issues identified in this workshop were: improved test methods to define refrigerant flammability, a better safety rating system for equipment, quantitative risk assessment and further quantification of the benefits of flammable refrigerants.

7.3.1.4 Next generation refrigerants

Researchers are continuing to search for pure refrigerants which could provide a longer term replacement for HCFC-22. Fluoroethers, fluoriodocarbons and three-carbon HFCs are some of the third generation refrigerants being investigated. Commercialisation of third generation refrigerants is expected to take 10 to 20 years. Very little technical information has been reported on third generation refrigerants.

7.3.1.5 Summary

Results so far indicate that HFC blends have good potential to replace HCFC-22 in air-cooled systems. These blends typically have at least one flammable component (usually HFC-32), and most of the blends show some zeotropic behaviour. Therefore, flammability, materials compatibility, fractionation and compressor and equipment design and manufacturing factors are issues that must be resolved before equipment using these blends can become commercially available. It is anticipated that unitary equipment using HFC refrigerants will begin to be commercially available in limited quantities in the 1996-1997 time frame. Widespread commercial availability of systems using HFCs will probably not occur until 2000-2005 (see section 7.6).

7.3.2 Alternative cycles

The desire to reduce emissions of chlorine based refrigerants has led to a resurgence in research, development and utilisation of heat and thermo-mechanical space conditioning systems. Significant advancements have been made in these technologies which warrant attention by the global energy and environmental community. The three broad classes of this technology are: ***thermo-mechanical*** **technology,** ***absorption and sorption*** **technology and** ***desiccant*** **technology. section 3.5 also provides additional discussion of alternative refrigeration cycles.**

7.3.2.1 Thermo-mechanical cycles

Alternative thermo-mechanical cycles can be broken into two broad categories: engine driven and non-fluorocarbon refrigerant cycles.

7.3.2.1.1 Engine driven cycles

Internal combustion engines have been used to power refrigeration systems since 1834. Currently, engine-driven systems are available in *ducted-split systems*, *non-ducted split systems* and *packaged* products. These products currently use HCFC-22 or HFC-134a as the refrigerant. It is anticipated that the alternative fluids developed for electric-driven vapour compression systems (section 7.3.1) will also be the refrigerants of choice these products.

7.3.2.1.2 Vuilleumier and Stirling cycles

The potential for ultra-low emission space conditioning continues to fuel research on Vuilleumier, sealed Stirling and kinematic Stirling cycles. The working fluid of these cycles is usually helium. In the Vuilleumier cycle /Ter91/, the system is driven by heat, usually by a gas fired burner. The gas fired Stirling cycles [sealed and kinematic] are almost identical to the Vuilleumier cycle except that they replace the Vuilleumier burner with a heat activated Stirling engine. The electric Stirling cycle uses an electric motor in place of heat to drive the cycle. The Vuilleumier cycle has a significant advantage in seasonal performance compared to the electric Stirling cycle machines because of its high heating efficiency. This cycle is currently being considered in several air source heat pumps under development /Ter91/.

Both of these cycles face significant design challenges to deal with high component costs and life expectancy. The maximum efficiency of free-piston Stirling coolers is expected to be approximately 60 percent of the Carnot efficiency /Ber93/. The current state of the art is 32 percent of Carnot efficiency in a domestic refrigerator application. Very little work has been reported on the efficiency of this technology in unitary air-conditioning equipment.

7.3.2.2 Absorption and sorption

Currently the industry is pursuing three approaches to heat driven air conditioning and heat pump cycles. These are *single effect absorption*, *GAX absorption* and *solid sorption*.

7.3.2.2.1 Single effect absorption

Direct fired absorption air conditioners are currently available in the global market. There are an estimated 200,000 in use within the United States. They use heat, usually from combustion of natural gas to create cooling. The refrigerant pairs in these absorption cycle machines are usually ammonia and water or lithium-bromide and water.

The absorption cycle begins at the evaporator with heat being absorbed from the air either directly or indirectly through a heat transfer loop. This heat boils the liquid refrigerant (ammonia or water) which migrates to the absorber where it is absorbed into solution with an absorbent (water or lithium bromide). This "mixed" fluid is then pumped to condensing pressure by a small solution pump. The high-pressure dilute solution enters the generator section of the unit where heat is added to drive the refrigerant from the solution. The now concentrated absorbent solution returns to the absorber and refrigerant vapour migrates to the condenser where it is liquefied by transferring heat to the outside air or cooling tower water loop and then is reduced in pressure by an expansion devise and returned to the evaporator to begin the cycle again. There are presently several drawbacks to residential-sized, ammonia or lithium bromide absorption cycle air conditioners. The first cost of this equipment is generally higher because the units are larger and use more material for a given capacity. They also require corrosion inhibitors to withstand the corrosiveness of ammonia and lithium bromide.

The efficiency of gas-fired absorption cycle designs for unitary applications is between 40 and 60 percent of vapour-compression system efficiency (including power plant and transmission losses). Secondary heat transfer loops required with ammonia can result in an additional efficiency reduction of 10 percent. In locations where the electricity-to-gas price ratio is high, the operating costs of absorption units are competitive with electrically-driven vapour-compression machines. Current research and development on absorption cycle systems promises to substantially increase the efficiencies of these systems.

Equipment utilising the single effect cycle is still widely used. Air cooled single effect units currently exist in sizes ranging from 10.5 kW to 17.5 kW. Since this equipment is heat driven it is particularly attractive to manufactures and others who have "waste heat" on hand. Additionally, the environmentally safe refrigerants and relatively low first cost of single effect equipment makes it attractive; however, the low efficiency of single effect equipment makes it impractical for many applications. The TEWI of single-effect absorption air conditioners is substantially worse than current HCFC-22 air conditioners /FIS93iii/ and future HFC air conditioners.

7.3.2.2.2 GAX absorption heat pump

A Generator Absorber heat exchange (GAX) cycle was first proposed in 1913. This cycle uses ammonia-water as the solution pair and takes advantage of the broad concentration (saturation temperature) range the fluid pair covers. This cycle, which is roughly twice as efficient as a single effect cycle, is currently being used in several air source heat pumps under development. Models should be commercially available in the 8.7 kW to 35 kW range in the next several years. The heat pump version of the GAX cycle uses valving to redirect an intermediate heat transfer fluid that couples the indoor unit to the outdoor absorption sealed system. The GAX heat pump is expected to have a TEWI comparable to HFC heat pumps.

7.3.2.2.3 Solid sorption

Research and development of solid sorption (ammonia/activated carbon) systems is also being conducted. Systems of this type were in commercial use in the 1920s in refrigerated rail cars and home refrigeration. Current research is improving the efficiency and first cost of these systems. However, the first cost of solid sorption systems is considerably higher than vapour compression systems because the units are larger and use more material for a given capacity. Ongoing research in solid sorption heat pump cycles has advanced to prototype testing. In the basic solid sorption heat pump cycle, a condenser, evaporator, and expansion valve function as they do in any vapour compression heat pump. Two carbon absorption "beds" provide the compressor function. One bed is heated while the other bed is cooled. The carbon being heated desorbs refrigerant, pressurising the bed. When the pressure reaches condenser pressure, the refrigerant check valve opens to allow the refrigerant to flow to the condenser as the carbon continues to be heated. The cooling of the carbon in the second bed depressurises that bed until the pressure is reduced to evaporator pressure, at which time the check valve from the evaporator opens to allow refrigerant to flow into the bed where it is adsorbed.

Another technology similar to ammonia/activated carbon is ammonia/mixed-salts chemisorption. This is operationally similar to solid sorption systems, and prototype systems are under development.

7.3.2.3 Desiccants

Desiccants are materials that attract and hold moisture from the surrounding air until equilibrium is reached. Lithium chloride, silica gel and zeolites are examples of common desiccants. Desiccants have traditionally been used to provide dry air for applications requiring precise humidity control. New desiccant materials are enabling engineers to design unique air conditioning cycles using desiccants.

7.3.2.3.1 Desiccant air driers

Desiccants have been used extensively in the past in dryer applications. A dryer is a device containing a desiccant material which is used to remove moisture and other substances which may contaminate some manufacturing processes. It was not until the 1960's that desiccants were considered for use directly in refrigeration applications.

The desiccant cycle is very different from the vapour-compression and the absorption cycle. Desiccants are materials (liquids and solids) that have a great affinity for absorbing or adsorbing water. Solid desiccants are usually bonded with a substrate in a paper form or on a metal foil, corrugated and rolled into a disk. This disk is then placed into a cassette which is divided into two sections: the dehumidification section and the regeneration section. The wheel is turned within the cassette at around 8 revolutions per minute. During a revolution of the wheel, an air stream is passed through desiccant material which causes the water vapour in the air to be adsorbed by the desiccant, thus drying out the air. The "wet" desiccant is then passed into the regeneration section where hot air (either direct-fired or indirect via a heat exchanger) drives the water from the desiccant material and exhausts it to the atmosphere. Sometimes an air-to-air heat exchanger system is employed downstream of the dehumidification section and up stream of the regeneration section to cool the dehumidified air and preheat the regeneration air.

Solid adsorbent, primarily silica gel and zeolite-based desiccant systems are starting to appear in a number of diverse applications, such as supermarkets, hotels in humid climates, hospitals, nursing homes and manufacturers that require strict humidity control. These are excellent applications for desiccant systems since the latent load (humidity) can be independently controlled. Desiccant dryer systems are also commonly constructed as packaged rooftop systems. While these systems remove latent heat from moist air they also add an equivalent quantity of sensible heat to the air stream. Therefore, these systems are generally used in conjunction with vapour compression refrigeration systems which remove the added sensible heat from the air stream. Desiccant systems have the capacity to process 1,000 litres/s to 16,000 litres/s of ventilation air.

7.3.2.3.2 Desiccant cooling cycles

New desiccant materials such as titanium silicate have such a strong affinity for water, that a practical desiccant air conditioning cycle can be developed. In this cycle, air is dried to a "super dry" state using these advanced desiccant materials. Because the latent heat of vaporisation of the water remains in the air, the air is very dry and very hot when it leaves the desiccant bed. Sensible heat exchange with re-generation air cools the conditioned air but it still remains warm and very dry. Evaporative cooling is then used to cool and re-humidify to the conditioned air to a comfortable level. This cycle is under development and limited commercial application is occurring. Since these systems are physically large their use has been primarily focused on commercial applications. These systems are expected to have low TEWI levels.

7.3.2.4 Passive cooling/evaporative cooling

In areas with low seasonal relative humidity and an adequate water supplies, evaporative cooling systems may be practical. These systems utilise the cooling effect of evaporating water. Evaporative cooling systems are very popular in the dry regions of tropical countries and are also used to supplement conventional vapour compression systems in staged cooling processes. These systems may sometimes create uncomfortable damp conditions unless coupled with a desiccant or vapour compression system to dehumidify the air-stream. Passive cooling and cooling by evaporation can be used in some geographic regions and form part of the HCFC replacement scenario. However, this technology is limited in its application to geographic regions having low average summer dewpoint temperatures.

7.3.3 Impact of alternative refrigerants and cycles

Of the options presented in sections 7.3.1 and 7.3.2 the introduction of HFC refrigerants into the market place will have the greatest impact on the industry requirements for HCFC-22 (sections 7.5 and 7.6) during the next 10-15 years. While alternative cycles are important and can have a long range impact on the usage of HCFCs, the early impact of these technologies will limited by long commercialisation and market acceptance intervals.

7.4 Retrofit

Retro-fitting of existing systems may be possible using a number of the refrigerant options currently being investigated as retrofit replacements for HCFC-22.

7.4.1 Retrofit issues

The suitability of a specific retrofit refrigerant will be determined by its attributes in relation to performance, need for system modifications, potential impact on system reliability and safety issues. The **performance** characteristics of any retrofit refrigerant will be a key factor in its suitability for retrofit applications. To be acceptable the retrofit refrigerant should exhibit similar capacity and efficiency to HCFC-22 (±10 percent). A retrofit refrigerant should require only minor system **modifications** and at a minimum should not require the replacement of the compressor or system heat exchangers. Retrofit options should only include refrigerants which provide system **reliability** similar to HCFC-22 systems. A significant drop in system reliability would be unacceptable. The reliability of the system with a retrofit refrigerant will be highly dependent on the compatibility of the new refrigerant and lubricant with the entire spectrum of materials used in system. Any incompatibility between the retrofit refrigerant/lubricant and the materials used in the system can result in high failure rates of the retrofit system. **Safety** will be one of the primary characteristics required of any retrofit refrigerant. Toxicity, flammability, handling requirements and operating pressure differences may rule out or limit many potential retrofit candidates. Considerable research and development is still required to locate a refrigerant capable of meeting all of these requirements.

7.4.2 Potential candidates

At least one promising retrofit candidate has emerged from the AREP evaluation. The HFC-32/125/134a zeotropic blend may be an acceptable retrofit refrigerant. Several retrofit field tests have been conducted with promising results. Other potential retrofit options are likely to emerge as research and development results become available.

7.4.3 Anticipated market impact of retrofit refrigerants

The need and market impact of retrofit refrigerants will largely be determined by the HCFC phaseout schedule and allowed service tail. An accelerated phaseout of HCFCs would increase the need for retrofit refrigerants. A phaseout schedule with a long service tail could reduce the need for retrofit refrigerants. Most of the installed population of air conditioners and heat pumps have an average service life of 10 to 15 years. Therefore a 10 to 15 year service tail would reduce the need for retrofit refrigerants. However, the search for suitable retrofit refrigerants should continue because they may provide high value to those that purchase air-conditioning products prior to the transition to the new refrigerants.

7.5 HCFC requirements

After more than 40 years of experience, HCFC-22 has generally been accepted as the most viable refrigerant for unitary air conditioners and heat pumps. However, by agreement of the Parties this refrigerant will be phased out in the mid/long-term. The future viability of non-chlorinated fluorocarbons, such as HFCs and HFC blends in new designs is promising. Once material compatibility issues have been resolved and design changes made to compensate for the new refrigerant's thermophysical properties, new equipment using HFC refrigerants should be commercially available.

However, until fully qualified substitutes are found, adequate HCFC-22 supplies will be needed to service new and existing equipment through at least the first decade of the 21st century.

Four factors must be considered when estimating future HCFC-22 requirements:
1. the anticipated demand in the world market for unitary equipment,,
2. the impact of recycling on the available supplies of HCFC-22,
3. the implementation rate of HFC refrigerants and other technologies into unitary equipment and,
4. changes in system design and servicing practices which will reduce the refrigerant charge quantities and refrigerant make-up requirements for unitary equipment.

Section 7.6 will present three scenarios designed to bracket future HCFC-22 requirements for Unitary Air Conditioners and Heat Pumps.

7.6 Usage forecast

World-wide use of HCFC-22 in 1990 is estimated to have been 180,000 metric-tonnes (see section 16) for all types of refrigeration applications. In 1990 approximately 74,000 metric-tonnes of HCFC-22 were used to manufacture and service the unitary air conditioners and heat pumps covered in this section.

Approximately 75% of this 74,000 metric-tonnes of HCFC-22 was used to service the installed population of unitary air conditioners and heat pumps. Of the total, only 33,000 metric-tonnes of HCFC-22 were used in 1990 for new equipment, leaving 75.7 percent of the annual usage to service existing products. A large portion of the high servicing requirement in the past can be attributed to servicing practices which generally included venting the entire system charge to the atmosphere when repairing refrigeration cycle components. In attempting to project HCFC-22 usage for the period 1990 through 2015 three sets of assumptions will be made - comparison of the impact of each set of assumptions will show the impressive effect that early phase-in of HFC or HC alternatives will have on the demand for HCFC-22. The scenarios do not assume a specific HFC or HC compound nor do they assume that HFC and HC are the only compounds which could replace HCFC-22 in these applications. The only assumption is that some environmentally safe refrigerant will replace HCFC-22. The following table shows the three HCFC-22 replacement scenarios assumed for this analysis.

Table 7.4 Assumptions for OEM refrigerant usage in new products

Year	Pessimistic		Most Likely		Optimistic	
	HCFC-22 %	Alternates %	HCFC-22 %	Alternates %	HCFC-22 %	Alternates %
1994	100	0	100	0	100	0
2000	93	7	91	9	58	42
2005	67	33	37	63	0	100
2010	10	90	0	100	0	100
2015	0	100	0	100	0	100

Table 7.5 *Reclaim rate assumptions (world-wide average)*

Year	World-wide Reclaim Rate (%)
1994	20
2000	50
2005	63
2010	77
2015	90

The analysis assumes a reasonably aggressive refrigerant reclamation effort by the world community. The assumptions on the percentage of refrigerant reclaimed during servicing and unit decommissioning are shown in Table 7.5.

The analysis predicts current and future populations of unitary products by using yearly unit shipment data (1964-1993) and assumed market growth rates to predict unit production for subsequent years. The product market growth rate assumptions are shown in Table 7.6.

Table 7.6 *Unit market growth-rate by product category*

Product Category	Assumed Annual World Market Growth Rate (%/Year)
Room Air Conditioners	4
Duct-Free Packaged and Split Systems	2.5
Ducted Systems	2.5
Commercial Systems	2.5

Once the annual production quantities were combined with assumptions of average product life (Gaussian distribution) they were used to predict the size of the current and future unit population. The amount of refrigerant in the unit population was calculated using the average charge quantities presented in section 7.2.

Table 7.7 *Product life assumptions*

Product Category	Mean Life (years)	Maximum Life (years)
Room Air Conditioners	10	15
Duct-Free Packaged and Split Systems	15	30
Ducted Systems	20	30
Commercial Systems	20	30

The product life assumptions were developed from historical failure rate data of a major HVAC manufacturer. The product life assumptions are shown in Table 7.7. The Mean Life is the average life of a given product type. The Maximum Life is the time after which 95 percent of the unit population has failed. Assuming a Gaussian distribution the standard deviation is one-third of the Maximum Life. Using these assumptions the model was able to predict the number of units of each category operating each year and the amount of refrigerant contained in the entire installed population. In addition the model utilised the three HCFC-22 replacement scenarios to predict total annual HCFC-22 requirements, amount of HCFC-22 obtained through reclamation and the net requirement for new HCFC-22. The following tables summarise the results of this analysis. Examination of Table 7.8 demonstrates the significant impact that the rate of insertion of new refrigerants into unitary products can have on the demand for new HCFC-22 production requirements.

The same model also predicts the quantity of alternative refrigerants required for each year. Table 7.9 shows the requirement for new alternative refrigerants and HCFC-22 by year.

Table 7.8 HCFC-22 requirements (1994-2015)

Year	Total HCFC-22 Requirement (metric-tonnes)			Amount from Reclamation (metric-tonnes)			New HCFC-22 Required (metric-tonnes)		
	Pessimistic	Most Likely	Optimistic	Pessimistic	Most Likely	Optimistic	Pessimistic	Most Likely	Optimistic
1994	88,144	88,144	88,144	3,038	3,038	3,038	85,107	85,107	85,107
2000	104,928	103,873	88,011	10,748	10,450	10,105	94,450	93,422	77,906
2005	109,253	89,066	55,507	15,996	15,306	13,717	93,257	73,759	41,790
2010	77,770	57,602	39,183	20,791	18,974	15,880	56,979	38,628	23,303
2015	53,922	39,470	24,880	23,835	20,339	15,332	30,086	19,132	9,548

Table 7.9 Comparison of alternative and HCFC-22 requirements (1994-2015)

Year	Amount of New HCFC-22 Required (metric-tonnes)			Amount of Alternative Refrigerants Required (metric-tonnes)		
	Pessimistic	Most Likely	Optimistic	Pessimistic	Most Likely	Optimistic
1994	85,107	85,107	85,107	0	0	0
2000	94,450	93,422	77,906	3,644	4,686	20,815
2005	93,257	73,759	41,790	20,765	40,849	72,450
2010	56,979	38,628	23,303	76,415	94,108	108,850
2015	30,866	19,132	9,548	125,204	136,674	148,374

7.7 Developing country considerations

Historically, the first air conditioning products to enter developing nations are large water or air-cooled chillers, intended for industrial or institutional use, and small room air conditioners. These products will probably utilise HCFCs as the refrigerant of choice if they are purchased prior to the phaseout date for HCFCs. The primary technical concerns of the developing countries are: adequate supplies of HCFCs to service existing equipment and equipment manufactured before the HCFC Phaseout date dictated by the protocol, adequate supplies of alternative substances and technologies and concerns over the cost and safety of the alternative refrigerants and technologies.

The life expectancy of most unitary equipment is approximately 20 years. The developing country concern over the availability of HCFCs to service existing equipment can be handled by allowing a sufficient service tail. The service tail should be at least 20 years to accommodate the developing countries need for service refrigerant.

The previous sections of this section provide an overview of the alternative refrigerants and technologies which are applicable to unitary products in both developed and developing countries. Data on the cost of these refrigerants and the redesigned systems in which they would be applied are just now being evaluated by researchers. Some of these technologies are ideally suited to developing countries. For example, *Evaporative Cooling* technology provides a very low cost alternative to vapour compression refrigeration in developing countries having hot arid climates. Technologies which are complex and in their early stages of development will probably be too costly or complex for consideration by developing countries.

Co-operative research efforts such as the ARI Alternative Refrigerant Evaluation Program provide a good source of technical information to address the cost, safety and performance issues of the alternative refrigerants for the developing countries. Workshops sponsored by the International Institute of Refrigeration provide another excellent source of technical information for developing countries.

Equipment and operating costs are real barriers to the entry of larger residential and commercial unitary products into a country. If the benefits of air conditioning are to be experienced on a wide scale, then those costs must be kept to a minimum. It is therefore important to develop alternative refrigerants and technologies which are both environmentally safe and cost effective. Technologies which are environmentally safe but also expensive and complex to implement would be a detriment to rapid conversion in developing countries. Obviously the ideal situation would be to develop a HCFC-22 substitute which costs, looks and performs the same as HCFC-22. None of the technologies currently available meet this ideal criteria. As the state of development progresses the alternative refrigerants and technologies available to developing countries will come closer to meeting this ideal criteria.

References

/Als/ Annual ***leak*** rate + annual requirement resulting from ***servicing*** of the refrigeration cycle

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/TEW/ The Global Warming Impact represented by the TEWI value considers the CO_2 emissions from the power plant. In the case of products which burn fossil fuels the actual CO_2 emissions of the product are used.

8 Air conditioning (water chillers)

8.1 Introduction

Comfort air conditioning in commercial buildings may be provided by two basic types of equipment; unitary air conditioners, and water chillers coupled with an air handling and distribution system. Unitary air conditioners cool and dehumidify by having the air pass directly through a coil containing an evaporating refrigerant. Water chillers cool water, or a water/antifreeze mixture, which then is pumped through a heat exchanger in an air handler for cooling and dehumidifying air. The previous section described unitary air conditioning. The present section discusses water chillers. Water chillers using the vapour compression cycle are manufactured in capacities from about 7.0 kW to over 35000 kW. Two types of compressors are used; positive displacement compressors and centrifugal compressors. From 7.0 kW up to 1600 kW, positive displacement scroll and reciprocating compressors may be used. From 140 kW up to 6000 kW, positive displacement screw compressors are used. From 350 kW to over 35000 kW, centrifugal compressors are used. Water chillers are offered in both air cooled and water cooled versions up through about 1500 kW in single units. Above this range, water cooled systems are available. Air cooled units become too large for convenient shipment as factory-assembled systems.

8.2 Current equipment and refrigerant combinations

HCFC-22 has been used in small chillers employing positive displacement compressors and in very large chillers employing centrifugal compressors. CFC-11 and CFC-12 have been used in large centrifugal chillers. Due to the CFC phaseout, CFCs 11 and 12 have been essentially replaced in new equipment production by HCFC-123 and HFC-134a, respectively. To date, no alternate has displaced HCFC-22 in the small and very large chillers.

8.2.1 Positive displacement compressors and chillers

HCFC-22 is an energy-efficient refrigerant used in most positive displacement compressors. The low volumetric flow rate and good transport properties of HCFC-22 allow use of compressors with relatively small displacements and heat transfer surfaces with minimal refrigerant flow area, keeping heat exchanger costs low, without leading to significant refrigerant flow pressure losses which reduce unit efficiency. In chillers units with reciprocating compressors it is common to use direct expansion evaporators (with refrigerant inside the tubes) which minimises refrigerant charge in the system.

HFC-134a is sometimes used in positive displacement water chillers. It has approximately 74% higher volumetric flow than HCFC-22 for the same refrigerating capacity, so larger compressors are needed. Pressure levels with HFC-134a are moderate, but high enough that in the USA and other countries code pressure vessels are required just as for HCFC-22.

8.2.2 Centrifugal compressors and chillers

HCFC-123 is an energy efficient refrigerant that meets the basic design requirements for low pressure centrifugal compressors. This accounts for its use in centrifugal chillers in the 350 to 5000 kW range. For larger capacities, the HCFC-123 compressor size becomes very large so refrigerants with lower volumetric flow rates such as HFC-134a and HCFC-22 are employed. HCFC-22 is used in the largest centrifugal chillers, from 1000 kW up to 35000 kW. The low vapour density of HCFC-123 results in large compressor impellers and piping. Maximum working pressure is low enough to exempt systems from having to meet most countries' pressure vessel code requirements. Pressure differences for leakage of refrigerant from the high side (condenser side) of the system to the atmosphere are low. The evaporator side operates below atmospheric pressure, resulting in the potential for air leakage into the system which will degrade its performance. High efficiency purge systems are provided to remove this air with minimal loss of refrigerant. The state-of the art purge systems lose less than 0.005 pounds of refrigerant per pound of air purged. This equates to approximately 0.005% of the system charge per year in a state-of-the-art chiller. HFC-134a is an energy efficient refrigerant used in centrifugal chillers from approximately 350 kW to 25000 kW capacity. HFC-134a systems operate at higher pressure than HCFC-123 systems and in the USA must meet pressure vessel code requirements. Pressures are above atmospheric throughout the system, so purge units and pressurising devices are not used. CFC-114 has been used in some centrifugal chillers, particularly those in naval vessels where it is desirable to have the evaporator refrigerant pressure above atmospheric pressure to prevent inward leakage of moisture-laden air, leading to corrosion problems. Naval centrifugal chillers are built in the range from 440 kW to 1400 kW. These applications are expected to be converted to HCFC-124 or HFC-236fa, or replaced by HFC-134a chillers.

8.2.3 Volume of equipment and refrigerant usage

Table 8.1 shows estimates of the number of water chillers in service world-wide in 1993. The table includes estimates of the total refrigerant charge in service in these chillers for the most commonly used refrigerants: CFC-11, CFC-12, R-500, HCFC-22, HCFC-123, and HFC-134a. Also, the approximate number of new chillers produced in 1993 is provided.

Table 8.1 Chillers in service

Chillers in Service	Approx No. of Units in Service	Refrigerant in Use (thousand tonnes)	1993 Shipments of New Units
Centrifugal and Screw chillers:			
CFC-11	110,000	37.5	0**
CFC-12	20,000	6.1*	0**
HCFC-22	35,000	13.8	3450
R-500	7,400	2.0	0**
HCFC-123	8,100	2.5	3725
HFC-134a	2,600	1.1	1550
Positive Displacement Chillers (air cooled and water cooled)			
-HCFC-22	455,000	22.5	33,500
-Other refrigerants	<-----------NOT	SIGNIFICANT	--------->

* Includes CFC-12 in R-500 chillers

** Excludes any CFC chillers that may be produced in Aticle 5(1) countries

Table 8.2 represents a "best guess" of the average capacity of water chillers employing different refrigerants as built in the U.S.A. in 1993 /Mar93/, and in Japan /Sah93/. The rest of the world is assumed to be similar to the weighted average of the U.S. and Japan.

Table 8.2 Average capacity of units produced in 1993

	Average Capacity (kW)
HCFC-123	1550
HFC-134a	1300
R-500	
HCFC-22 recips (air & water cooled)	150
HCFC-22 screw and centrifugals	1300

Table 8.3 indicates the average amount of refrigerant per unit of cooling capacity of U.S. and Japanese manufacturers for chillers built in the 1990-95 period /Sah93/ /Cal91/. The rest of the world is assumed to be similar to the weighted average of the U.S. and Japan.

Table 8.3 Average refrigerant charge in units in service

	kg/kW
CFC-11 and HCFC-123	0.25
CFC-12, R-500, and HFC-134a	0.33
R-500	0.33
HCFC-123	0.22
HFC-134a	0.32
HCFC-22 (screw and centrifugal)	0.31
HCFC-22 recips (air- and water-cooled)	0.33

Table 8.4 presents estimates of the amounts of refrigerants required in 1993 for charging new chillers for operation. Additional amounts are used to make up for leakage and losses during servicing. Leakage occurs because of ageing or failure of seals, fittings, and gaskets, pressure relief valves, and purge units (low pressure refrigerants). Losses during servicing can occur through accidental spills, failure to remove all of the charge from a system before it is opened up for service, or inability to recover and reuse all of the refrigerant removed from a unit.

In the United States, these losses have been dramatically reduced in response to the Clean Air Act [CAA]. The CAA /USF93/ requires evacuation of systems using CFCs or HCFCs to prescribed pressure levels depending upon the nature of the application and the refrigerant, and it requires that detected leaks in systems containing more than 20 kg of refrigerant must be repaired if the leak rate exceeds 35% of charge per year for commercial refrigeration and industrial chillers or over 15% per year for all other applications (such as air conditioning). Similar regulations will be required in 1995 to implement the Clean Air Act Amendments of 1990 as they apply to the "venting, release, or disposal of any substitute substance for class I (i.e., CFCs) or class II (i.e., HCFCs) substance ...". This will include HFCs among other regulated chemicals.

Table 8.4 Refrigerant usage

	New Chillers (tonnes)
CFC-11	0
CFC-12	0
HCFC-22	3000
R-500	0
HCFC-123	1450
HFC-134a	650

8.3 New equipment and refrigerants

The Montreal Protocol and subsequent amendments have resulted in a high level of activity in the industry to phaseout the CFCs and the HCFCs with moderately high ODPs

[HCFC-22 in the case of chillers]. Of cource, the search for alternates has resulted in a renewed understanding that ideal refrigerants do not exist.

The theoretical cycle efficiencies and chemical compatibility of the alternates are generally not as good as those of the refrigerants that they replace which were selected decades ago for efficiency and compatibility. This is complicated by the fact that some of the leading alternates, such as many of the HFCs, have relatively high direct effect (emissions) global warming potentials. The selection of alternate refrigerants requires a balance between the global environment issues of ozone depletion and global warming and terrestrial safety issues such as bioactivity and flammability. Even within the single issue of global warming, there is need to account for the direct effects of the release of the chemicals to the atmosphere and the indirect effect that the use of the chemicals has in relation to the chemicals they replace. One indirect effect is increased use of fossil fuel energy caused by less efficient refrigerants, with the consequent increase in CO_2 release to the atmosphere. As a further complication, the distinctions between direct and indirect global warming effects are highly dependent upon the application [being very different for a foam blowing agent than for a refrigerant]. A resolution of this particular factor has been proposed in the form of a Total Equivalent Warming Impact [TEWI] which combines the direct and indirect effects over a selected integration period (e.g., 100 years). For chillers, the indirect effect dominates over the direct effect when low, achievable, leak rates are used in the analysis.

8.3.1 Positive displacement compressor chillers

Significant changes in positive displacement chiller refrigerant selections and chiller designs are beginning to occur as a result of ozone depletion concerns. Traditionally, HCFC-22 has been widely used as a working fluid for high pressure positive displacement chillers, and CFC-12 has been used as the working fluid for intermediate pressure positive displacement chillers. (As known, both of these refrigerants are scheduled to be phased out)

8.3.1.1 HCFC-22 as an interim refrigerant

Due to its low ODP, relative to the CFCs, HCFC-22 has been viewed for several years as a part of the solution to the problems posed by phaseout of CFCs. At present, the phaseout of individual HCFCs is being managed differently in various countries. In the United States, the phaseout of HCFC-22 for new equipment is scheduled for the year 2010.

The planned HCFC-22 phaseout has led to intense activity to find and characterise appropriate alternates. Much of this work has been under the auspices of the AREP program of ARI (see section 7). The refrigerants being considered include various HFCs, zeotropic and azeotropic blends of these HFCs, ammonia, and one or more HCs. The refrigerants which appear to be most promising in terms of their ability to satisfy the performance and safety criteria are the blends of the HFCs. The blends which seem best for use with flooded evaporators, common in chillers larger than 700 kW, are those which are azeotropes such as HFC-32/125 which has a much higher pressure than HCFC-22.

Considerable work remains to be done on finding suitable replacements for HCFC-22, finding appropriate lubricants for each application, and making design changes required by differences in characteristics between HCFC-22 and the replacements. The challenge is magnified by the need for a fluid which closely approximates the properties of HCFC-

22 to service existing systems, and the need to find the fluid with the best balance of properties for use in new systems. At this time, it appears as though no single refrigerant, or blend of refrigerants, will satisfy both applications.

Azeotropic mixtures are under consideration as HCFC-22 replacements because they tend to act as single component refrigerant [i.e., the vapour and liquid composition at a given temperature and pressure is constant]. However, no azeotrope has been found which matches the pressure-temperature relationships of HCFC-22. Blends of HFC-32 and HFC-125 have capacities and COPs similar to HCFC-22 in a DX system, but at a significantly higher pressure. Substantial product redesign and retooling, with associated major financial investments, would be required to use these HFC-32/HFC-125 blends in chillers. Zeotropic mixtures offer the greatest flexibility in blending refrigerants to approximate the physical and thermodynamic properties of HCFC-22, in particular, the general trend of the pressure/temperature relationships. Thus, they are the most likely candidates for "drop-in" replacements for HCFC-22 in DX systems. In DX evaporators, the glide characteristic of zeotropic mixtures can be used to advantage in counterflow heat exchange. The glide also can be accommodated in the traditional cross-flow air-side heat exchangers of air-cooled chillers. It is only in the flooded evaporators of large chillers that the glide cannot be accommodated.

Mixtures with appreciable glides have not been considered suitable for use in flooded evaporators which predominate in larger chillers. A flooded evaporator is essentially isothermal and isobaric, so the "glide" tendency is exhibited as a composition change between the liquid and vapour phases in the evaporator [instead of the temperature glide observed in a DX heat exchanger]. These tube-in-shell evaporators keep the refrigerant on the shell side so that the water can be confined to the inside of the tubes, thus facilitating periodic cleaning of the water tubes to eliminate efficiency-destroying mineral build-up.

Based on a very extensive search of alternatives, it is clear the *there is no drop-in replacement for HCFC-22 in chillers with flooded evaporators today, neither at medium term.* One implication of this is that further acceleration of the phaseout of HCFCs would have serious consequences for the stock of HCFC-22 chillers in service at the time of the phaseout, if servicing needs are not adequately dealt with (see section1.5.3).

8.3.1.2 HFC-134a as the primary replacement for CFC-12

HFC-134a is being used in positive displacement water chillers as a zero-ODP substitute for CFC-12. The volumetric flow characteristics of HFC-134a are similar to those for CFC-12, so the compressor and equipment sizes are similar. Thus, chiller costs are not significantly affected by the change from CFC-12 to HFC-134a, except for the increase in refrigerant and lubricant costs. The direct global warming effect of HFC-134a is about 15% of that of CFC-12 (100 year time horizon). The theoretical cycle efficiency is about 2% lower than that for CFC-12. However, the excellent heat transfer characteristics of HFC-134a more than make up for the lower cycle efficiency.

(Note: HFC-134a can be pressed into service to replace HCFC-22 in some applications at a significant loss of capacity (up to 35%). However, HFC-134a does not offer a significant advantage in either direct or indirect global warming potential).

8.3.1.3 Other refrigerants

A number of other zero-, or near-zero-, ODP refrigerants with volumetric flow rates in the range suitable for positive displacement chillers have been suggested. Examples are HFC-32, HFC-125, HFC-152a, HC-290 (propane) and R-717 (ammonia) (see also section 5 and 6). These refrigerants are not attractive to designers of water chillers for commercial buildings. HFC-32 has a very high condensing pressure. HFC-125 has a low critical temperature, so it has poor efficiency as a refrigerant. HFC-125 also has a higher direct GWP than HCFC-22 or HFC-134a. The refrigerants HFC-32, HFC-152a, HC-290 [propane] and R-717 [ammonia] are flammable. Use of flammable refrigerants in commercial building chillers would require isolation of machinery rooms from the buildings, and in the U.S.A., thousands of building codes would have to be changed. The application concerns with ammonia are even more complex because the refrigerant is toxic as well as flammable. The flammability concerns can be allayed by combining the HFC and HC refrigerants with non-flammable refrigerants in proportions which make the blend non-flammable. This is usually done at the expense of performance compared to the best-performing of the un-blended refrigerants. The challenge of using blends is discussed in 8.3.1.1 above.

8.3.2 Centrifugal chillers

Centrifugal compressors are the most efficient technology in their range of applications, from 200 to several thousand tons refrigeration capacity [500 to perhaps 35000 kW]. Water chillers employing these compressors are designed for specific refrigerants. The traditional refrigerants have been CFCs-11 and 12, HCFC-22, and R-500.

The CFCs have been replaced by HCFC-123 and HFC-134a, respectively, but HCFC-22 is expected to be used in new equipment for at least another decade. The relative condensing pressures at 38°C are 0.145 MPa for HCFC-123, 0.963 MPa for HFC-134a and 1.461 MPa for HCFC-22. The lowest pressure refrigerant (HCFC-123) is usable in the smallest centrifugal chillers (down to 500 kW); the highest pressure refrigerant (HCFC-22) is usable in the largest chillers (up to 35,000 kW); and the intermediate pressure refrigerant (HFC-134a) bridges the gap, penetrating into the ranges of both the low and high pressure refrigerants. Chillers employing all three of these refrigerants are available with coefficients of performance ranging from 5.4 [0.65 kW/ton] to 6.4 [0.55 kW/Ton]. Manufacturers have plans for further improvements in COP's.

Direct refrigerant substitution can be made only in cases where the properties of the substitute refrigerant are nearly the same as those of the refrigerant for which the equipment was designed. There is no possibility for substituting HCFC-22 into CFC-11 or CFC-12 chillers, for example. In the case of HCFC-123, hermetic motor designs satisfactory for CFC-11 may not be compatible with the chemistry of HCFC-123. This has led to development of new motor insulation's. Other materials of construction had to be checked and, in some cases, changed. Similarly, the mineral oil lubricants used in CFC-12 systems are insoluble in HFC-134a. New lubricants had to be developed for use with HFC-134a. Additional problems are found in trying to retrofit units operating in the field with alternative refrigerants, as discussed later in section 8.4.

Another issue with the new generation of refrigerants is their toxicity. The new refrigerants which are being used, or being considered for use, have undergone the most extensive toxicity tests to which refrigerants have ever been exposed. These tests have been so extensive because the chemicals are used in other applications, such as foam blowing, where routine occupational exposure levels are orders of magnitude greater than the routine exposure levels from refrigerants in closed systems. HCFC-123 has been assigned an AEL (allowable Exposure Level) for continuous occupational exposure of 10 to 30 ppm, more than an order of magnitude greater than levels measured in machinery rooms by the U.S. EPA. For chiller system servicing, the more relevant measure is the EEL (Emergency Exposure Level). This has been set at 1000 ppm for HCFC-123, the same as the AEL (Acceptable Exposure Limit) and/or TLV (Threshold Limit Value) for CFC-11, CFC-12, HCFC-22 and HFC-134a.

Other refrigerants suggested for centrifugal chillers are HFC-152a, HFC-143, and the fluoroethers E-134, E-143, and E-245ca. These compounds are either flammable or have no toxicity assessments at this time and in some cases have very limited thermodynamic data available. These compounds would have to be considered speculative at this time. HFC-245ca is a potential long-term alternative to HCFC-123. It has a similar vapour pressure and appears to have good stability and low toxicity. HFC-245ca may be less aggressive to motor insulation and, thus, may have advantages as a retrofit refrigerant for CFC-11 chillers. An important concern is that while it is nonflammable in dry air, it can form weakly flammable mixtures in humid air. More work is necessary to determine the efficiency of HFC-245ca as a refrigerant and to define any fire risks associated with its use in chillers. Nonflammable azeotropes containing HCFC-123 are another alternative for reducing the amounts of HCFC-123 used in chillers. One azeotrope is 92% HCFC-123 and 8% normal pentane. This mixture reduces the amount of HCFC-123 required by roughly 20% because of the low density of the pentane. It may also have efficiency and capacity advantages in retrofits of CFC-11 chillers. An azeotrope of 70% HFC-245ca and HCFC-123 is another possibility. Further investigation is necessary to evaluate these azeotropes as refrigerants.

Two isomers [ea and fa] of HFC-236 are being considered as replacements for CFC-114 which is used in speciality applications such as naval vessels. These chemicals are not produced in commercial quantities, and have not been subject to toxicity test nor extensive materials compatibility tests. Thus, their possible commercial use as replacements for CFC-114 is probably several years away at the earliest. In the U.S.A., shipboard chillers for the Navy are being designed for HFC-134a.

8.3.3 Alternative technologies

For purposes of this report, alternative technologies will be divided into two categories: (1) the vapour compression cycle that uses a working fluid based on non-halocarbons or using a mixture of refrigerants (see section 8.3.1), and (2) a refrigeration machine that operates on a principle other than the vapour compression cycle.

The principal non-halocarbon working fluids for alternate vapour compression systems are ammonia, various hydrocarbons [butane, propane, etc.], or other "natural fluids" such as CO_2 or H_2O. Examples of non-vapour-compression water chillers are machines based on the absorption cycle.

CO_2 and H_2O represent two rather extreme examples of "natural refrigerants". CO_2 requires very high pressure equipment; condensing pressure is 7.208 MPa at 30°C. This is far beyond the state of the art for conventional refrigeration equipment [e.g., HCFC-22, generally regarded as a high pressure refrigerant, has a condensing pressure of 1.192 MPa at 30°C]. The high pressure is a particular challenge due to the need for safety margins that are a significant multiple of the design working pressure [In the U.S., this is a multiple of 5 to the maximum design pressure]. H_2O is at the other extreme. It is a very low pressure refrigerant, with a condensing pressure of 4.246 kPa at 30°C. In addition, the reactivity of water makes this a very challenging material to use. Traditionally, water has been used in speciality applications with steam jet aspirators, not with vapour compressors. However, commercialising is ongoing for water compression chillers for specific applications (and this development needs careful evaluation in the coming years).

Other refrigerants such as SO_2 and methyl chloride had a long history of use until they were replaced by the CFCs, due to safety concerns with these "natural refrigerants". For example, in Cook Country, Illinois [Chicago] there were at least twenty-nine methyl chloride poisonings from refrigerant leaks between August 1928 and July 1929 /Cag93/.

Safety concerns exist for the flammable hydrocarbons. They are undesirable for water chillers because of the large refrigerant charge in these machines. In unitary products, the additional cost for changes required to obtain U.L. approval in the U.S. has been reported to be on the order of 30%, exclusive of any set-aside for additional liability coverage /ARI94/.

Both the risk and capital investment necessary for redesign; retooling; training in operation, maintenance and service; marketing; etc. are particularly significant in equipment as large as water chillers and in a world where the customer is used to an equipment life of 25 years or more. Based on such practical considerations, it seems that the only alternative technologies that may be feasible for the current timetable are those which already exist in production. Of these, only three seem to be suited for water chilling: (1) the vapour compression cycle using ammonia as working fluid, (2) the absorption cycle, and (3) zeotropic refrigerant mixtures (covered in 8.3.1.1, above).

8.3.3.1 Ammonia chillers

Ammonia (R-717) is an excellent refrigerant thermodynamically. It has been in continuous use in a variety of applications longer than CFCs so there is a wealth of practical experience in the manufacture, operation, and maintenance of ammonia machinery systems.

Most modern experience and applications are for large refrigerated warehouses. With some development and adaptation it is certain that ammonia systems could be applied to some water chilling needs. However, this assumes that the public and, in the USA, the multitude of political jurisdictions, can be satisfied that the ammonia systems can be made safe even under emergency conditions such as building fires and/or earthquakes. Most important is the establishment of a building code that will be acceptable to both the safety officials (e.g., fire marshals) and those concerned with costs (e.g., architects). For development and widespread acceptance by the thousands of political jurisdictions of the U.S., such a process could take a decade or more, if indeed it is possible at all.

Since ammonia is toxic and flammable, its current refrigerant applications are primarily limited to large systems that are isolated from the general public. Recommended practice (ASHRAE Std. 15 and ISO/DIS 5149) limits the use of ammonia in public buildings to those systems that utilise a secondary heat transfer fluid, thus confining the ammonia to the machine room where alarm and venting devices can ensure safety. Systems requiring more than 500 kg were prohibited from use in public buildings under earlier versions of ASHRAE-STD-15. Ammonia's chemical reactivity with copper in the presence of water prevents its use with hermetic compressor systems, but current research on motor winding coatings may remove this limitation. More detailed information about ammonia applications and properties can be found in section 5

8.3.3.2 Absorption chillers

Absorption is a tried and proven technology that is mass produced and well supported with a cadre of experienced technicians. Heat-activated absorption water chillers are a viable alternative to the vapour compression cycle for some installations. Three of the four processes that comprise the traditional refrigeration cycle are used in the absorption system. The compression process is replaced by an "absorber" and a "generator" which are complemented by an evaporator and a condenser. The working fluid is either ammonia with a water absorber, the most common, or water with a lithium bromide absorber.

Traditionally, single-stage absorption systems could not compete with electric vapour compression systems on an economic basis. Applications were typically limited to sites that could utilise waste heat as the primary energy source. Such sites might be co-generation systems where waste engine heat or steam was available. In a few localities, natural gas rate structures are particularly favourable compared to electric rate structures, making direct-fired, single-stage absorption viable. A key factor in the economic viability of absorption is the penalty on electric vapour compression chillers imposed by electricity demand charges [demand is continuously averaged over an integrating interval (typically 15 minutes), and a demand charge per kW is applied over the full billing period, or over a longer period, up to the following 12 months.]. Demand charges are common in the United States for commercial and industrial customers. Other local peculiarities, such as a shortage of electrical generating capacity or high initial connection charges, such as exist in Japan, also favour the choice of absorption.

This past decade, two-stage absorption chillers have been developed and produced with primary-energy-based efficiencies that approach 50% to 60% of those of vapour compression systems. Three-stage absorption systems are being developed to achieve efficiencies even closer to vapour compression systems. However, absorption chillers are inherently larger and considerably more expensive than vapour-compression chillers so absorption systems have had only limited market success in the West [U.S. production was 416 units in 1993 (about 250 thousand tons/ 870 MW), up from 387 units (235 thousand tons/ 822 MW) the year before]. In Japan, where electric rates are much higher, absorption chillers dominate the market.

A factor which will limit changeovers from CFC vapour compression chillers to absorption is the inability to retrofit in many existing buildings because the access ways are not large enough to allow for the absorption chiller to be delivered to the existing machine room.

8.4 Retrofits

8.4.1 General comments

As shown in Table 8.1, there is a large stock of chillers now in service which employ CFCs. No substitute refrigerant can be used as a "drop-in" for CFCs with the exception of HFC-134a in some R-500 systems. As CFC production is reduced and ultimately phased out, the functions performed by these chillers will have to be supported in one of the following ways:

Retain: continued operation with CFCs in conjunction with containment procedures and equipment to reduce emissions, using refrigerant which is:

- available from production, until production ceases or is insufficient
- available after being recovered from other units converted to non-CFCs or retired.

Retrofit: modification to allow operation with alternative refrigerants (HCFCs or HFCs).

Replace: early retirement/replacement with HCFC or HFC chillers.

The retrofit options which exist for each chiller are dependent upon the specific refrigerant for which the chiller was originally designed. When any retrofit is performed, it is recommended that the machinery room be updated to the requirements of the latest edition of ASHRAE-STD-15. It is also recommended that the manufacturers of the equipment be actively involved in any retrofit program.

8.4.2 HCFC-123 for CFC-11 in centrifugal chillers

HCFC-123 became available in 1989 to retrofit existing CFC-11 chillers. It is a more aggressive solvent than CFC-11. Non-metallic materials may have to be replaced with materials which are compatible with HCFC-123. Materials used in motors of older hermetic chillers may not be compatible with HCFC-123, putting motor reliability at risk or requiring motor replacement. System capacity may be reduced between 0% and 20% depending on the matching of the compressor to the load and heat exchanger effectiveness. Change-out of the compressor to a higher-capacity model or purchase of additional chillers may be necessary. Cycle efficiency will be reduced about 1-2%. An optimised conversion designed for the specific machine will minimise the loss of capacity and efficiency.

8.4.3 HFC-134a for CFC-12 in centrifugal chillers

HFC-134a became available in 1989 for retrofit in centrifugal chillers. Its use requires about 15% higher tip speeds than CFC-12, so impeller and/or gearbox replacement may be necessary. Alternatively, the heat exchangers can be re-tubed to reduce head pressure. In either case an engineered conversion is necessary to minimise loss of capacity and efficiency. Typically, the mineral oils used with CFC-12 are not miscible with HFC-134a. Polyolester oils are now being widely used and appear to have overcome compatibility problems. However, mineral oil concentrations in HFC-134a systems should be reduced to less than 3-5% even with POE oils, or else heat exchanger performance will be reduced. Some desiccants (e.g., activated alumina) commonly used in CFC-12 systems are not compatible with HFC-134a.

8.4.4 HCFC-124 for CFC-114 in centrifugal chillers

HCFC-124 has been suggested as an alternative to CFC-114 in centrifugal chillers such as those used in Naval applications. HCFC-124 requires operation at higher pressure levels, higher compressor speeds, and smaller impeller diameters than CFC-114. HCFC-124 is not suitable for use in existing CFC-114 systems in most cases because the pressure levels will exceed design ratings and complete compressor replacement is necessary.

HFC-236fa is being considered as a potential retrofit refrigerant to replace CFC-114 in naval chillers. Operating pressures will be closer to those of CFC-114 than with HCFC-

124. Energy efficiency considerations, equipment modification needs, refrigerant stability, materials compatibility, and toxicity issues were under investigation in 1994.

8.4.5 Replacements for HCFC-123, HFC-134a, or HCFC-22

There are currently no satisfactory replacement refrigerants for use in existing chiller equipment designed for HCFC-123 or HFC-134a. However, pressures to accelerate the HCFC phaseout schedule and pressures to control HFCs, are of concern to the chiller industry because there are no drop in replacements for these refrigerants. The major candidates that might be suggested tend to be HFCs which would be under the same environmental pressures as HFC-134a.

For equipment now using HCFC-22, zeotropic and azeotropic mixtures of HFCs are being developed. The previous comments concerning new equipment in section 8.3.1 explain the problems with zeotropes which prevent their use in many existing chillers. In particular, it should be re-emphasised that zeotropic blends will not work with flooded evaporators which are used in the overwhelming percentage of large chillers [essentially all centrifugal chillers and screw chillers over 700 kW use flooded evaporators].

8.5 HCFC requirements

8.5.1 General comments

HCFC refrigerants such as HCFC-123 and HCFC-22 have much lower ozone depletion potentials than CFCs, and HCFC-123 has a very short atmospheric lifetime [less than 2 years]. Accelerating HCFC phaseout schedules may force the use of technologies that are less efficient or more costly. No further acceleration appears warranted at this stage.

Both the HCFCs and HFCs are required as transition and long term refrigerants respectively until at least the 2020-2030 period. HCFCs and HFCs are needed to allow the most rapid phaseout of CFCs in critical applications such as air conditioning and refrigeration where the HCFCs and HFCs are the best alternatives available.

Improved design and maintenance of systems to reduce leakage, design to minimise refrigerant charge quantities in systems, improved service practices, and reclaiming of refrigerant during servicing are practical and reasonable ways to reduce the emissions of HCFCs and HFCs into the atmosphere, thus minimising adverse environmental effects. To varying degrees in different countries each of these practices is being implemented.

8.5.2 Current uses of HCFCs

HCFC-123 has a very low ODP. Its current uses are limited to centrifugal chillers, where it offers the highest known theoretical efficiency of all HCFCs and HFCs. This high efficiency contributes to a low indirect global warming potential. HCFC-123 has a low direct GWP as well, giving a low Total Equivalent Warming Impact [TEWI]. The very low ODP and GWP effects of HCFC-123, coupled with its ability to displace CFC-11 in new chillers and in most existing low pressure chillers, require this refrigerant to be available at least until 2030 to speed the transition away from CFCs, and to service the machines now being built with HCFC-123 throughout their useful lives.

Based on efficiency and cost, HCFC-22 is the best presently available choice for positive displacement chillers, and for large centrifugal chillers its efficiency approaches that of

HCFC-123. The extensive use of HCFC-22 chillers today, plus the use of HCFC-22 chillers to displace CFC chillers in manufacturers' product lines, indicate that HCFC-22 will be needed to service these chillers through their 25-30 year life until an alternative is readily available. As indicated above, zeotropes cannot be used in those chillers which employ flooded evaporators, and this is the majority of large [over 700 kW] HCFC-22 chillers.

8.5.3 Alternatives to HCFCs

HFC-134a will play an important role in the transition away from CFCs, particularly as a replacement for CFC-12. HFC-134a has zero ODP, low total equivalent warming impact [TEWI], and offers long term solutions. However, HFC-134a is not able to overcome the need for HCFC-123 and HCFC-22. From a global warming and investment standpoint, it is desirable to retain HCFCs as transition chemicals and not count on HFC-134a exclusively to bridge the time period until efficient alternatives to HCFCs are ready for widespread use.

There are no other good near-term alternatives to the continued use of HCFCs. The situation with alternatives is summarised below:

> Alternatives to HCFCs available within the 1996-2000 time frame are likely to be limited to HFC-125, ammonia, flammable HFCs, or mixtures of refrigerants made nonflammable.
>
> Ammonia and the flammable HFCs or mixtures are not usable for new equipment unless installation practices and building codes are revised extensively in the most significant global chiller markets. These revisions are difficult and time-consuming. In some countries such as the USA, equipment manufacturers, operators, and insurers will be extremely concerned about flammable refrigerants because of the high risk of litigation.
>
> HFC-125 and some refrigerant mixtures are not desirable because they do not yield energy efficiency levels comparable to presently-available chillers. Lower efficiency leads to increased indirect global warming /Fis91/. HFC-125 and some mixtures have high direct GWP contributions as well.
>
> Water chillers are being commercialised and may be feasible for specific applications.
>
> Zeotropic refrigerant mixtures complicate heat exchanger design because the boiling temperature varies with composition. Service work is more difficult because it is necessary to measure and balance the composition.
>
> None of the alternatives discussed above can be used in existing chillers now in service. They are unacceptable for one or several reasons; material incompatibility, safety, basic system design, refrigerant flow rates and power requirements, and pressure levels.

8.6 Future need for CFCs

Much of the existing stock of installed equipment will need CFCs for servicing. It is too early to know whether recycling efforts will be effective enough to provide an adequate supply of CFCs. All possible efforts need to be done until 2000 to allow a certain amount of equipment owners to service their chillers.

As of the end of the first quarter of 1994, it is estimated that there have been something on the order of 3000 CFC chillers (out of about 75,000 to 80,000 installed) in the United States converted to HCFCs or HFCs. This is believed to be short of the rate of conversions that will be necessary in order to avert a shortage in the years ahead.

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9 Transport refrigeration

9.1 Introduction

The technical options report in 1991 outlined the range of equipment used for transport refrigeration, including trucks and trailers, railcars, ships, and intermodal containers (TOR 91). It also included the use of refrigeration and air conditioning on board all types of ships, and air conditioning systems in buses and passenger trains. The transport refrigeration market is growing steadily, at a rate of around 6% per annum, and this is expected to continue for the rest of the current decade.

Of necessity, much of the statistical data has to be estimated, and the likely errors of estimation are more than the likely changes over 2-3 years, so in several cases the 1991 estimates have been retained. Wherever better figures have been obtained in the course of the reviewing process, these have been incorporated. Qualitative changes since 1991 have included an almost universal acceptance of HFC-134a for new intermodal containers, and moves to HFC-134a or HCFC-22 or blends, such that in 1994 the use of CFCs for new equipment will have virtually ceased. This is only possible because of the continuing availability of HCFC-22, for which no proven alternatives are available. 1993 marked the return of ammonia as a refrigerant for cargo ships. Only time will tell whether this proves to be a commercially viable option.

For existing equipment, the development and proving of reliable retrofit options for older units has been time-consuming, and it is likely that the costs involved will result in premature scrapping of a substantial amount of plant. A certain amount of CFC plant will be maintained from recovered refrigerant, but much recovery is local for local re-use, so accurate statistics on quantities are not available.

Related topics not covered in this section include the following:-

1) CFC and HCFC use in the production of insulation foams for transport equipment. A quantity of the order of 4000 tons of blowing agent is used annually, which is rapidly transferring from CFCs to HCFCs.

2) Air conditioning of drivers' compartments in road vehicles, which is considered to be part of the automotive air conditioning sector.

3) Fixed refrigerated installations at ports.

4) Use of Halons for marine fire-fighting. This is now restricted to the use of existing stocks and recycled product.

Apart from the use of ammonia in a few new ships, there has been no significant adoption of not-in-kind alternatives in the transport sector, but research continues in a number of areas which may be of value in the longer term. Development of hydrocarbon blends has been announced in mid 1994; these will need full evaluation of technical performance and proper risk assessments before their potential in transport applications can be fully assessed.

9.2 Current use

9.2.1 Ships

9.2.1.1 Refrigerants in use

CFC and HCFC uses in ships are as follows:

- CFC-11 in marine air conditioning, especially of cruise ships.
- CFC-12 marine air conditioning and provision room refrigeration in ships, and near universal use in pre-1993 refrigerated containers (considered separately below).
- HCFC-22 marine air conditioning and provision room refrigeration in newer ships, most central cargo refrigerant plant, fish freezers and fishing boat refrigerated storage, liquid gas tanker re-liquefaction plant.
- CFC-114 in some air conditioning plant including some naval vessels.
- CFC-502 occasionally for low temperature refrigeration.
- NH_3 is also used for cargo refrigeration and air conditioning using an intermediate heat exchange fluid in a small number of ships.

9.2.1.2 Quantitative data

There are approximately 33,600 ships of all types in excess of 300 gross tonnes. Air conditioning and provision room refrigeration plants typically contain 150 to 300 kg of refrigerant fluid. Central cargo refrigeration plants might contain 2 to 4 tonnes.

The fully refrigerated cargo fleet (excluding container ships) has continued to grow steadily since 1985. At the start of 1994, the total fleet comprised around 880 vessels with a refrigerated cargo space around 8 million m^3. Approximately two thirds of the fleet is less than 15 years old and will be expected to operate beyond 2004, as 25 years is generally the planned life of a ship. In 1993, for the first time in several years, the number of vessels hardly changed, as scrapping balanced new buildings. However, as the new ships are mostly larger, total capacity increased by around 0.13 million m^3.

If refrigerated container ships are included, at the end of 1993 there are approximately 1170 vessels of over 2,800 m^3. which are specifically designed to carry refrigerated cargo. If smaller cargo ships are included, the total could be nearer 1500 vessels.

The total CFC pool in all ships over 300 gross tonnes is estimated at 9000 tonnes. Current annual emissions cannot be assessed with any degree of precision, but may be around 2000 tonnes. No estimates could be made for the many smaller vessels like fishing boats, large pleasure boats, ferries, etc.

The total HCFC pool may be around 33000 tonnes. Emissions of which a large proportion is due to fish factories and fishing ships, may be around 15000 tonnes annually.

The special operating conditions on naval vessels can lead to relatively high refrigerant leakage rates and maintenance requirements, which can exceed the equivalent of a full charge per year.

9.2.1.3 ICS code of practice

The International Chamber of Shipping now lists CFCs as a recognised source of atmospheric pollution, and has issued a management standard as follows:-

a) review maintenance procedures and leakage detection procedures to minimise the release of ozone depleting gases into the atmosphere from existing plant;

b) where possible, utilise CFC recovery and recycling facilities;

c) where practicable, utilise alternative forms of refrigerant gases and insulation materials;

d) where appropriate, encourage and support research into design improvements, new systems and alternative refrigerants.

9.2.2 Railcars

In 1991 there were approximately 75,000 refrigerated railcars in use world-wide, of which about 75% were in the former Soviet Union. There are usually two refrigeration units per railcar, each of nominal 10 kW power input and each containing 15 kg of CFC-12. This gives a total pool of about 2250 tonnes of CFC-12. Maintenance requires of the order of 5 tonnes per year only. Assuming a life of 11 years, average annual production is 6000 cars per year, requiring 90 tonnes of CFC-12. This excludes the US fleet, which is expected to be operated without replacement into the next century. It was anticipated that by the end of 1992 all new production would be operating on HCFC-22. The wide range of ambient temperatures encountered by these units may make it difficult to convert existing units to alternative refrigerants, but there is no reported experience.

9.2.3 Containers

Refrigerated intermodal containers are of two types. Integral containers are fitted with a refrigeration unit, usually electrically powered. Insulated containers require the use of external refrigeration equipment, either clipped on small units or large air handling units with press-on connectors. Container numbers are often expressed in "t.e.u." which refers to "twenty foot equivalent units", a unit of volume corresponding to a twenty foot ISO container. As many units are of a volume of 2 t.e.u., there can be confusion between t.e.u. numbers and actual container numbers. Sometimes the "f.e.u." (forty foot equivalent unit) equivalent to 2 t.e.u.s. is used. At the end of 1993, there were 252 000 integral containers (400 000 t.e.u.) and 80 000 insulated containers (90 000 t.e.u.) in use world-wide, according to the best available estimates. Approximately half of this equipment is less than 5 years old and would be expected to operate until the year 2003 or after. Refrigeration units contain around 5 kg of CFC-12, with a total pool of about 1660 tonnes. Losses due to leakage and repair are difficult to assess, and were previously may be lost additionally due to poor handling and maintenance practices. Increasing use of refrigerant recovery equipment in repair depots should lead to reductions in overall use, but no specific data are available. The above figures do not specifically include marine clip-on refrigeration units (using CFC-12 in older units and HFC-134a in new equipment) or port 'tower' installations (some of which operate on CFC-502). However, the numbers of installations are relatively small compared to the number of container refrigeration units, and given the uncertainties in the data, they would not add significantly to the totals.

Newer equipment operates on CFC-12, HCFC-22, or as the preferred option, HFC-134a. Production rates were around 40 000 units per year in 1992 and 1993, and are expected to fall to perhaps 30 000 in 1994, of which maybe 6000 will operate on HCFC-22, the remainder using HFC-134a. The HCFC-22 units are predominately in Japanese based trades, where there is often a demand for lower cargo temperatures. There have been no significant sales of CFC-12 machines since 1993. It is estimated that by the end of 1994 there will be 40 000 containers operating on HFC-134a. A reasonable estimate of annual refrigeration use is 200 to 400 tonnes of CFC for maintenance and repair plus 160 tonnes of HFC-134a and 33 tonnes of HCFC-22 for new manufacture. At mid 1994, probably 1000 to 2000 CFC-12 machines have been converted to HFC-134a. The rate of conversion is slow due to cost, potential loss of performance, uncertainties about reliability, and continual changes to legislation.

9.2.4 Swap bodies

Swap bodies are transport units which are between trailers and containers. They are not trailers, as they do not include a chassis and road wheels. They are not ISO containers, as they are not suitable for high stacking. Frequently they incorporate extendible legs so that a road or rail chassis can easily be withdrawn from under them. At present there are no more than 10 000 refrigerated swap bodies in use, and these are included in the total for road vehicles as they generally use the same types of refrigeration units.

9.2.5 Road transport refrigeration

The total world fleet is estimated at 850,000 to 1,250,000 vehicles, of which about 30% are trailer units, 40% are independent truck units, and the remainder are smaller units driven from the truck engine. Total manufacturing rates are around 100,000 per year. The trailer units typically have a refrigeration capacity (at -18°C cargo space temperature in 38°C ambient) of 6 to 10 kW, with a refrigerant charge around 10 kg. Truck units have a capacity of 1.5 to 5 kW, and about 6 kg charge, the smaller units (down to 800 watts) may have 3 kg charge typically.

Refrigerants CFC-12 and CFC-502 have been traditionally used and units operating on these refrigerants are still in production. In countries with rapid CFC phaseout programmes, current production uses HFC-134a, HCFC-22, R-401B and R-404A with R-404A increasingly being seen as a preferred option for all but the smallest units. The total CFC pool world-wide is estimated at 6000 to 8000 tonnes, with a service requirement of 1200 to 1600 tonnes per year. This service requirement has been reduced due to reduction of leakage's and improvements in service procedures, but because of the onerous operating conditions is still around 20% p.a.

There is a considerable movement of older, larger vehicles from Western Europe to the former USSR states, and no information has been collected concerning the maintenance

9.2.6 Transport air conditioning

There are an estimated 250,000 to 300,000 buses and coaches with air conditioning, of which approximately half are in North America. They mostly use CFC-12 or R-502, and the refrigerant pool is estimated at 300 tonnes of HCFC-22 and 3000 tonnes of CFC-12 or R-500. As most existing systems use long lengths of polymeric tubing, leakage rates are relatively high. Annual maintenance requires perhaps 200 to 400 tonnes of HCFC-22 and 1200 to 2400 tonnes of CFC. Rail air conditioning systems number at least 75,000, over half of these being in Asia. In Japan, there are approximately 35,000. These mainly operate on HCFC-22, with a pool of about 1500 tonnes and an annual use of maintenance of 300 tonnes.

9.3 New equipment options

For all types of transport equipment, non-CFC options are now available. Some equipment operates on HCFC-22, some on HFC-134a, and there are moves towards alternatives such as R-404A. R-401B, R-402A, R-402B, R-403B and other non-zero ODP. blends are seen as transitional fluids for application in some equipment. HFC-32 based blends have yet to be considered and evaluated in transport applications. It would therefore be fair to say that the situation is in a state of flux, and the preferred long-term refrigerants are uncertain for applications in which CFC-502 was previously used. There appears to be a consensus in favour of HFC-134a for traditional CFC-12 applications at the time of writing. New equipment designed for the new refrigerants is able to match the performance of traditional equipment. As a replacement for HCFC-22, there is no obvious single candidate today which meets all the essential criteria. Chlorine-free mixtures of HFCs may provide solutions, with a compromise necessary between energy efficiency, flammability and direct global warming potential. Blends containing various components from HFC-134a, HFC-125, HFC-143a and HFC-32 are being tested in various applications. Although some results are positive, another two years of testing is needed to satisfy all the parameters of importance to users.

In all applications, the new refrigerants require more rigorous handling techniques and are more expensive. Many of them require new lubricants which are sensitive to moisture vapour to a much greater extent than traditional mineral oils.

If manufacturers could recommend use of new compressors with HCFC-22 and polyol ester lubricants, a changeover at a later date to proven alternatives would be a simple drop-in procedure.

Regarding alternative technologies for transport refrigeration there are no realistically efficient alternatives to vapour compression refrigeration in the short to medium term future. Some research is in progress on air cycle refrigeration, but there is no immediate prospect of application.

A few large systems on ships have now been produced using ammonia (NH_3) (R-717), with indirect brine systems and a limited refrigerant charge kept within a protected space. Suggestions have been made regarding possible future use of carbon dioxide (CO_2)(R-744) in vapour compression systems. Experimental developments of Stirling cycle units and Peltier effect units in the past have failed to demonstrate the ability of these systems to meet realistic refrigeration capacity and efficiency targets for transport refrigeration [illegible] loss refrigerants (either liquid nitrogen or carbon dioxide) power supply is available or for delivery trucks in noise sensitive areas. The energy requirements of liquefaction of gases are such that, in global terms, this is not an alternative to be encouraged on a large scale. The use of flammable hydrocarbon refrigerants has been proposed for smaller transport applications. Full evaluation of technical performance and a proper assessment of safety considerations will be necessary before these can be adopted.

9.3.1 New ships

As mentioned above, ammonia has been used for the first time in many years on a few ships built in 1993. This is only possible for indirect systems with a limited charge in a protected space if newly-developed safety codes are to be met, and there are costs associated with the necessary protective equipment which preclude its use in smaller systems. For air conditioning, food storage, and central cargo plant on board ship, HCFC-22 is virtually universal for new equipment.

9.3.2 Other new equipment

New road transport equipment from major producers is moving rapidly into HCFC-22, HFC-134a and R-404A, but no doubt many smaller producers in the world are still using CFC-12 and R-502. Whilst the total use of refrigerant for new production can be estimated at 500 tonnes annually, details of the current proportions of different refrigerants are not available.

For containers, nearly all new equipment now uses HFC-134a, though a few manufacturers can still supply equipment operating on CFC-12 or HCFC-22. Current manufacturing rates may require 120 tonnes of HFC-134a per year for new container equipment, plus 30 tonnes of HCFC-22.

New plant for ships' air conditioning and provision rooms now uses HCFC-22, and sometimes HFC-134a. Use of new blends is at present only on an experimental basis.

9.3.3 Maintenance and refrigerant recovery

New equipment is designed with minimisation of refrigerant leakage, both in service and during maintenance, as a prime objective. However, the effectiveness of these designs is dependent on the quality of technicians, and moves toward compulsory testing and competency certification of refrigerant handlers are not universal. Countries such as Australia have had relevant legislation for some years, other countries seem happy to depend on standards and codes of practice combined with wider environmental protection legislation. The amount of CFC refrigerant being recovered for re-use is difficult to estimate. Widespread legal restraints on release to atmosphere have been effective, but much recovery is for local re-use and is not therefore recorded. The alleged labelling of new refrigerant as recovered in order to avoid import restrictions is a further complication.

9.4 Retrofits

Fluids being considered or used for transport equipment retrofits include HCFC-22, HFC-134a, all the blended refrigerants of the ASHRAE R-400 series, and hydrocarbon blends. The extent to which there are problems in retrofitting varies greatly from unit to approved. Whilst HCFC-22 and R-403B can be used with traditional mineral oils, R-401B requires an alkyl benzene oil, and both HFC-134a and R-404A need polyolesters. Costs of oil flushing vary between oil types, and even within types there are variations in additives between lubricant manufacturers, not all of which are approved by all machinery manufacturers. Compatibility of sealing materials, of driers, and of expansion valve power heads needs consideration in each case. For conversion from CFC-12 to HCFC-22, modifications to overcome higher power, temperature, and pressure requirements are necessary.

In some cases, the conversion to HCFC-22 is eased by reducing the number of compressor cylinders operating. Where this is not possible, a conversion to HFC-134a may require a change to a larger compressor to maintain performance, and a transitional HCFC blend may provide a more economic solution. In particular cases, advice must be sought from the manufacturer of either the refrigeration unit or the compressor.

Depending on the nature of the retrofit, costs for vehicle or container units could vary from a few hundred to a few thousand US dollars, and may not be worth while for some older equipment. For larger plants running on CFC-12 with open drive compressors, conversion to HCFC-22 will require lower compressor running speeds or compressor replacement, but this is feasible and for ships with 15 or more years remaining life, is likely to be an economic proposition. The blended refrigerants may not be available to the extent required for international refrigerated transport. It is not just a question of being able to be ordered in any country, but a matter of being in stock at every relevant depot. For marine containers, availability on board ships is also necessary. Without this level of availability, the ability to carry out emergency servicing cannot be ensured.

Zeotropic blends with a wide temperature glide may be unsuitable for some transport applications. On temperature control, transport refrigeration is very demanding. A container refrigeration unit has a full width evaporator capable of holding cargo at -25°C in 50°C ambient. When this is used to hold critical chilled cargo at -1 ± 0.5°C in a 0°C ambient, the problems of temperature uniformity across the width of the coil are difficult enough with a pure fluid, and are made much worse if there is a high temperature glide.

9.5 Servicing

Transport refrigeration equipment should be checked for proper operation before every journey, and should only require the attention of a service engineer if there is a problem. Modern equipment frequently includes microprocessor controllers with detailed self-checking algorithms which make the task easier. In the past, there is evidence to suggest that over-zealous "servicing" has led to problems and more refrigerant loss than was strictly necessary. If there are suspected problems, it is essential to use competent, trained technicians with a sufficient knowledge of available equipment and available refrigerants. Procedures must minimise refrigerant loss and, where applicable, must include recovery of old refrigerants for recycling. Users should insist on proper records of refrigerant use. In areas of the world where there are registration schemes for technicians or contracting companies, these should be encouraged in order to ensure uniform and adequate standards of competence.

10 Mobile air conditioning

10.1 Introduction - developments since 1991

The accelerated phase-out of CFCs has brought about a corresponding acceleration in the introduction of HFC-134a in new vehicles to the extent that full conversion in Developed Countries was completed during 1994. Accelerated phase-out also created the need to address retrofitting CFC-12 vehicles much earlier than expected, resulting in a larger population of CFC-12 vehicles to deal with and a considerably shortened time frame for development and implementation of alternatives. Accordingly, OEM's and the service industry turned their engineering attention toward developing retrofit technology. Assisting in the process is the Society of Automotive Engineers (SAE) which has developed and released standards and recommended practices for retrofit refrigerant acceptance criteria and service procedures designed to minimise refrigerant cross-contamination during both normal service and retrofit operations. SAE documents are intended to supplement OEM retrofit recommendations.

10.1.1 Replacement refrigerant HFC-134a

OEM vehicle manufacturers have selected HFC-134a as their recommended retrofit refrigerant, although other candidate refrigerants may exist and find use in the global marketplace. Refrigerants other than HFC-134a have not been supported by vehicle OEM's for several reasons: (1) they offer no advantage over HFC-134a; (2) there is essentially no time to adequately test and commercialise additional refrigerants; (3) they create the need for all service outlets to purchase yet another set of tools and equipment; and (4) they represent additional refrigerants with which the service industry must deal, thereby posing the real threat of contaminating existing CFC-12 and HFC-134a supplies, service equipment and MAC systems. Activities are currently underway to develop cost-effective and reliable retrofit procedures using HFC-134a in advance of CFC-12 shortages. This report deals principally with the technology and costs associated with servicing CFC-12 vehicles in the face of a dwindling CFC-12 supply and includes information from, and recommendations for, both Developed and Developing Countries.

10.2 Current CFC-12 use

Approximately 288 million vehicles with CFC-12 MAC systems are in existence today. The global distribution of these vehicles is estimated to be as follows: 84% (241 million) in the Developed Countries, 50% (142 million) in the U.S., and 15% (43 million) in the Developing Countries. These vehicles have historically required new CFC-12 for service at a rate of approximately 0.40 kg per year per vehicle-on-the-road /DuP88/. With the advent, and widespread use, of on-site recycling and appropriate service practices, this need can be reduced to about 0.19 kg per vehicle, a substantial savings.

Recycling CFC-12 and HFC-134a at the job site is a currently available technology and is a reality in many developed countries. Such recycling serves to capture refrigerants for reuse that would have otherwise been lost to the atmosphere. The cost to purchase recycling equipment is recovered at retail by the savings associated with not having to purchase as much new/make-up refrigerant.

A typical piece of recycling equipment in the United States costing US $ 2000, can be amortised at the rate of approximately US $ 44 per kg of recycled refrigerant 12 at retail. Given a recovery rate of approximately 0.45 kg per vehicle, the equipment cost can be recovered after about 100 service jobs. Following such cost recovery, recycling provides income that can be used to maintain and/or replace the equipment as necessary. This example, while applicable to the United States, may or may not prove as compelling in other countries where the wholesale cost and retail price of refrigerant differs (Figures 10.1 and 10.2). For widespread recycling to occur in any given country, it must be cost justifiable and accessible or required by law (Table 10.1)

10.3 Options for new vehicles

Due to the imminence of CFC-12 phase-out, no real opportunity exists for OEM's to have a significant impact on CFC-12 usage beyond those improvements already in place, e.g., conversion of new vehicles to HFC-134a, the use of less permeable hose materials, better service methods, recycling equipment and service technician training. In addition to the conversion of new vehicle production to HFC-134a, OEM's world-wide continue to study the needs associated with retrofitting CFC-12 vehicles to HFC-134a and are in the process of releasing retrofit kits and recommended procedures.

10.3.1 Implementation of HFC-134a in mobile A/C systems

Full implementation of HFC-134a in MAC systems was completed during calendar year 1994. Possible exceptions to this might be some Developing Countries choosing to continue using CFC-12 due to a lack of infrastructure to support HFC-134a systems. These countries might import CFC-12 vehicles directly, manufacture such vehicles themselves, install aftermarket CFC-12 systems, or charge vehicles with CFC-12 that were originally delivered without refrigerant. This possible scenario emphasises the importance of establishing an infrastructure to service HFC-134a vehicles in these countries. Existing SAE and draft ISO documents can be used to provide guidelines for such infrastructure development (SAE, 1994). See the appendix for a listing of appropriate SAE documents. HFC-134a is the unanimous global choice for new vehicle air conditioning. Should all new vehicles in Developed and Developing countries use HFC-134a, this will end the use of ozone-depleting substances by the original equipment mobile air conditioning industry, thereby satisfying the original goal of the Montreal Protocol. The issue of global warming potentials associated with the use of refrigerants, while outside the aegis of the Protocol, has been, and continues to be, a consideration in the alternate refrigerant selection process. The substitution of HFC-134a for CFC-12 in MAC systems reduces the direct global warming potential by 84% based on a 100 year integrated time horizon. Any global warming contribution would be further minimised with increased emphasis on conservation, recycling, recovery and reclamation, use of low loss service charge valves and fittings, and improved A/C hoses and seals.

10.3.2 Future mobile A/C systems

Interest continues in the development of more environmentally "benign" refrigerants for all applications; yet, given the time required for commercialisation (notably toxicity testing and end product design and application considerations), such a refrigerant, as yet not identified, would not be expected to be *commercially* available and in use in new vehicle MAC systems until well beyond the year 2000.

The development and commercialisation of alternate cycles for mobile air conditioning is also expected to be well beyond the year 2000, due to attendant technical hurdles (i.e., system size and weight, vehicle application, system durability, effect on vehicle fuel economy) and the fact that their use would require enormous investment in entirely new manufacturing facilities and service facilities equipment and tools. Attempts to identify and commercialise a more "benign" refrigerant suitable for use in existing equipment designs appear to be a better direction, and one worth pursuit.

It should be noted that the time required to bring a vehicle to market, from design to production, is on the order of 3-4 years. Accordingly, vehicle OEM's will be finalising designs for their 1999 model year product offerings during calendar year 1995. This means that actual commercialisation of a new refrigerant or a new refrigeration cycle will not occur until at least 3 to 4 years after the technical hurdles have been cleared and it has been proven to be commercially viable (see section 10.7).

10.4 Retrofitting the CFC-12 fleet

10.4.1 General comments

Developing cost-effective and timely retrofit technology is a formidable task. Current MAC systems using CFC-12 were specifically designed for use with CFC-12 and its lubricant, mineral oil. In fact, compressors meet customer expectations because the compressor and lubricant, have been co-engineered. In the case of CFC-12 and mineral oil, the compressor benefited from a well-characterised chemical reaction between the chlorine in the CFC-12 and the hydrogen in the mineral oil that forms an anti-wear film on demand on wearing parts to reduce wear. The introduction of HFC-134a, or other refrigerant, not containing chlorine, requires a lubricant specifically designed to overcome the loss of anti-wear activity with which the compressor was originally designed and the higher operating pressures characteristic of HFC-134a. The many changes in compressor designs necessary to be able to use HFC-134a in new vehicles are a testimonial to the value of the CFC-12/mineral oil reaction. Other complementary system changes included increased condensing capacity to reduce operating pressures. In summary, unique lubricant properties are required that are system and compressor specific to retrofit MAC systems and the task is to identify and develop lubricants that specifically address the needs of each compressor design. The implication here is that different lubricants will be required to meet the needs of the many different types of CFC-12 MAC systems in use today. To illustrate this point, while the OEM's have all used a lubricant from the PAG (polyalkylene glycol) class of lubricants for their new HFC-134a systems, Volvo has since chosen a polyol ester for retrofit due to an inherent incompatibility of PAG's with seal materials previously used in CFC-12 systems. This may only be the "tip of the iceberg" for the service industry, which will undoubtedly experience great difficulty in handling the many lubricants likely to be required. To compound this concern, using a lubricant not recommended by the vehicle OEM can result in compressor damage.

10.4.2 Retrofit requirements

Presently, no chemical or blend of chemicals exists that has been proven to be able to directly replace CFC-12 without substantial retrofit costs. HFC-134a has been selected as the vehicle OEMs' mainstream retrofit refrigerant because its interaction with common system components and materials has been well characterised. Since it is already in use in new vehicles, it does not increase the number of refrigerants the service industry must deal with. The existence of multiple refrigerants in the field is a real concern, due to the potential for refrigerant cross-contamination and the significant additional expense of purchasing tools and equipment to handle each refrigerant. In fact, service equipment suppliers are now developing equipment (targeted to retail for under US $ 1000) to identify/analyse refrigerant contained in incoming vehicles to prevent unwanted contamination.

10.4.2.1 Retrofit refrigerant

Properly testing and qualifying a new refrigerant has historically required in excess of three years to ensure reliable system performance and durability. Retrofit refrigerants require additional testing for use in, and effect on, existing CFC-12 systems. Given the imminent need to retrofit vehicles, there is essentially no time left to identify, develop and commercialise other retrofit refrigerants. The notion that a "drop-in" refrigerant may one day magically appear is not realistic and may even delay the application of retrofit technology currently developed while users wait for such a refrigerant to appear in the marketplace. Since no chemical or blend of chemicals has been shown to be of greater benefit than HFC-134a for retrofit, expending resources in this area for such a transient need as retrofitting is simply not justified. An acceptable retrofit refrigerant (HFC-134a) has been chosen by the industry stakeholders - the job that remains is to continue to develop proper retrofit procedures to implement its use. With the selection of HFC-134a as their retrofit refrigerant choice, MAC system manufacturers are not expected to devote many efforts at short term toward developing other retrofit refrigerants.(maybe this will be more stimulated by chemical companies and/or other initiatives). Based on the results of local retrofit fleet testing, some countries in the Asia Pacific region have decided to include R-401C along with HFC-134a as a retrofit option for existing CFC-12 vehicles. Programs have been initiated to train service technicians in proper use and handling of this refrigerant. Based on local market conditions and customer requirements, retrofits to R-401C are being performed by a network of trained technicians using upgraded A/C components as required.

10.4.2.2 Retrofit cost for HFC-134a

Estimated general requirements and associated service-level costs for retrofitting vehicles are presented in Table 10.2 and remain similar to those reported in the 1991 technical assessment. Notable exceptions to this are the need to more fully evacuate the system to minimise residual CFC-12 prior to adding HFC-134a to the system and the addition of appropriate service fittings to add the refrigerant and labels to identify the system as having been retrofit to accept HFC-134a.

Given the fact that MAC systems are custom-designed to the needs of each vehicle model, actual retrofit requirements (and costs) to maintain acceptable performance and durability will vary widely. Noteworthy is the fact that retrofitting means not only altering the original system design intent, but doing so on systems of varying age, prior usage and maintenance profiles all of which conspire to present vehicles of unknown condition to the service industry. Because retrofitting places greater demands on the system (e.g. higher operating pressures), the useful life of system components not changed during retrofit may be shortened. This places both the consumer and the retrofitter at risk of secondary failure and unexpected additional costs. In fact, virtually all OEM's have stated that their systems were designed for CFC-12, work best with CFC-12 and recommend using CFC-12 as long as possible to provide optimum system performance and durability.

A least-cost scenario, presented in Table 10.2 as incremental costs, includes the recovery of CFC-12, extended evacuation to remove residual CFC-12, adding retrofit lubricant, service fittings and labels; all at an estimated cost of US $ 78. Higher cost scenarios, involving additional component replacements and/or additions (e.g., high pressure cut out switch, compressor, condenser, condenser fan, and system controls) are likely to be necessary for a significant percentage of vehicles to maintain acceptable durability and/or performance. It should be emphasised that these costs are exclusive of, and in addition to, the cost of repairing the problems that originally brought the system in for service. These repairs are estimated to average US $ 260 /MAC93/. MAC system manufacturers and component suppliers are expected to provide retrofit information and components to the service industry in a timely manner. Actual costs will vary from country to country due to differences in labour and parts costs. These costs may offset each other somewhat in Developing countries where labour costs are lower but parts costs are higher.

10.4.3 Retrofit/ obsolescence scenario and costs

The phase-out of CFC production will force consumers whose MAC systems need repair and who cannot access new, recycled or reclaimed CFC-12 to either retrofit or obsolete their systems. Retrofitting represents an immediate cost to the consumer while obsolescence involves reduced vehicle value at resale, loss of personal comfort and, while difficult to quantify, a potential reduction in driver "alertness" generally associated with the use of air conditioning, especially during long trips /Vol92/.

10.4.3.1 Retrofitting the CFC-12 fleet

Retrofitting will be driven by the need to service vehicles whose systems are not operational. The number of vehicles forecast to require retrofitting in the U.S. is 40 million, (Table 10.4). Given that 59% of developed countries' air conditioned vehicles reside in the U.S., an estimated 68 million vehicles will require retrofitting in developed countries. The number of vehicles that must be retrofitted or obsoleted each year was calculated as shown in Table 10.4 for the United States and then extrapolated to a represent the global condition (Figure 10.3). Because each country's approach to dealing with the CFC phase-out will differ, the validity of such an extrapolation is somewhat questionable. Given this, the approach and assumptions used herein are intended to provide a model for determining the impact of CFC-12 phase-out on MAC systems for any country for which the necessary input information is known or obtainable.

Societal cost for retrofitting in developed countries (not including normal repair costs) is the number of vehicles retrofit times the average cost of a vehicle retrofit. While the least cost retrofit is estimated to be US $ 78, the average cost is expected to be higher, taking into consideration additional components recommended by the OEM's to maintain acceptable performance and durability.

10.4.3.2 Retrofit activity

Some voluntary retrofitting is expected in 1994 and 1995 as the cost difference between continued use of CFC-12 and retrofitting to HFC-134a diminishes. An estimated 10-15% of vehicles, in for service, will be retrofitted at the owner's option. Forced retrofitting on a larger scale due to CFC-12 shortages is not expected to begin until 1996, although some retrofits due to spot shortages may occur earlier in Developed Countries.

10.4.3.3 CFC-12 supply

Refrigerant availability in any given use sector is difficult to forecast. Historically, the mobile air conditioning service industry has required a significant amount of refrigerant, which it will continue to require until the fleet is retrofitted or no longer in service. (See table 10.3) The phasing out of CFC production will likely find those service industries using CFC-12 competing for the same limited supply, depending upon such factors as the extent of CFC-12 stockpiling, the ability to offer reliable and economical retrofitting, and the amount of retrofitting prior to cessation of CFC production.

The major assumption that generated retrofit estimates in Figure 10.3 is that sufficient CFC-12 will be available to the MAC service industry during 1994 and 1995 based on CFC production allowances, CFC-12 inventories, and voluntary retrofitting, followed by CFC-12 shortages after production ends and inventory draw-down begins. This shortfall will create a need answerable by system retrofit or system obsolescence. An estimated 40 million retrofits are forecast to occur in the U.S. over the period 1994-2002, with over half of these during 1997-2000. Substantial inventories of HFC-134a compatible components will be required by the service industry to be able to fill this need.

10.4.3.4 Exported CFC-12 vehicles

Some developed countries have historically exported their older vehicles to other countries, a practice which, if followed, may eliminate the need for wholesale retrofitting of CFC-12 systems in the country of origin and create a corresponding need in the recipient country.

10.5 Infrastructure requirements

Developed countries are capable of moving away from the use of CFC-12 in MAC systems at reasonable cost because they are capable of manufacturing, importing, and servicing new vehicles containing HFC-134a and they have the service and parts infrastructure to be able to retrofit CFC-12 vehicles to HFC-134a (or other substitute refrigerant). Conversely, developing countries may have neither the wealth to manufacture/import and service significant numbers of new HFC-134a vehicles nor the established infrastructure to effectively retrofit existing CFC-12 vehicles, Indeed, many countries have a relatively simplistic approach to servicing MAC systems, to the extent that many such services are essentially "gas-and-go", without the benefit of leak repair.

10.5.1 Global mobile A/C survey

A survey was sent to representatives of developed and developing countries individually, and to representatives of the E.U., for the purpose of gaining insight as to their handling of refrigerants and the CFC issue as relates to mobile air conditioning. Survey results are summarised in Table 10.1. A positive finding is that recycling of CFC-12 and HFC-134a used in MAC systems is becoming increasingly prevalent around the world. Also worthy of note is the wholesale cost and retail price of these two refrigerants in these countries (see Figures 10.1, 10.2). These refrigerant costs and prices support the cost-effectiveness of refrigerant recycling cited in section 10.2. In all but the United States, the consumer price for HFC-134a far exceeds that of CFC-12, which has the unfortunate effect of making CFC-12 the refrigerant of economic choice for most of the world.

10.6 HFC and HCFC demands 1995-2000

An estimate of HFC-134a demand in developed countries over the period 1995-2005 is shown in Table 10.3 and is based on OEM production and service needs for new HFC-134a vehicles and amounts required for retrofitting to HFC-134a per Figure 10.3.

Because the level of global acceptance for refrigerants containing HCFCs is not known, HCFC demands for use in MAC systems have not been estimated.

10.7 Next generation equipment (15 year time horizon)

With respect to eliminating the use of ozone depleting substances in MAC systems, few near-term refrigerant choices, useful with today's vapour compression cycle equipment, are available and appear to be restricted to HFC-134a, flammable refrigerants, such as hydrocarbons and HFC-152a, or refrigerant blends.

Blends proposed to date have all contained ozone-depleting substances which makes their use unattractive in addition to inherent problems associated with fractionation of the blend constituents during system operation leading to significant system control problems. In addition, selective loss of blend constituents due to permeation losses through hoses and seals continuously alters the blend composition. This adversely affects both MAC system performance, compressor durability and the ability to recycle these refrigerants "on-site".

10.7.1 Industry future direction

HFC-134a, which is non-flammable, contains no chlorine and is therefore not expected to contribute to ozone depletion, has been selected by automobile manufacturers as best choice for MAC OEM and retrofit applications. Supportive of this decision is the Alternative Fluorocarbons Environmental Acceptability Study /AFE91/ conclusion that, following a review of alternate refrigerants from a total energy cost standpoint, "the total equivalent warming impact (TEWI) for HFC-152a is essentially the same as for the non-flammable refrigerants." This equivalency arises from the belief that, to ensure occupant safety, flammable refrigerants require an additional heat exchanger, fluid pump and heat transfer medium to prevent the refrigerant from entering the passenger compartment, all of which add to total system energy requirements. Should means be found to utilise flammable refrigerants safely without the need for a secondary coolant loop, such refrigerants could provide an attractive alternative to HFC-134a for future OEM applications.

It should be noted that existing CFC-12 MAC systems are not designed to safely handle flammable refrigerants and attempts to market such refrigerants for retrofit application have met with resistance from governmental agencies (notably the U.S. Environmental Protection Agency and U.S. Department of Transportation). For this application, flammable refrigerants represent an unacceptable hazard to both consumers and repair technicians.

10.7.2 Future alternate refrigerant and cycles

The potential applicability of alternative refrigeration cycles as they relate to the global warming issue has generated much interest, especially within academic and environmental circles. Global refrigeration and air conditioning technology "workshops" have been held to discuss alternative cycles and their potential applications /Bre93/ /Wie93/. In addition, AFEAS and the U.S. Department of Energy are currently collaborating on evaluating the technology status and energy usage of selected alternatives. Topics under review are carbon dioxide, zeolite/water, ammonia, HFCs (e.g., 152a and 134a), air cycle, Stirling cycle, etc.

10.7.3 Transcritical carbon dioxide systems

The aforementioned global workshops noted ongoing efforts to improve the efficiencies of fluorocarbon vapour compression systems (today's system) and recommended a closer look at the transcritical carbon dioxide system. This system is similar to today's vapour compression system but operates at much higher pressures (100 atmospheres versus 20-25) due to the low critical temperature of carbon dioxide. Historically, these systems found use on ocean-going vessels but were later replaced (by CFC equipment) due to their inherent inability to operate efficiently when using warm tropical waters to cool the condenser. The assessment at the Wiesbaden, Germany conference was, "Carbon dioxide systems for mobile air conditioners provide an interesting alternative for HFC-operated compression systems, although many questions arise concerning the development time and about the impacts of the very high operating pressures on safety, design, and reliability. Therefore, this option was not considered feasible before the end of the decade. Nevertheless, application of carbon dioxide systems could have a tremendous impact." Noteworthy is the fact that this type of system has only been evaluated in the laboratory. Carbon dioxide systems have yet to be studied on a real vehicle under actual operating conditions. Application of such a system to cars and trucks would pose many challenges, not the least of which includes maintaining adequate condensing at high ambients, maintaining compressor performance at the very high pressure differentials (causing piston "blow-by") that will be encountered, and containing the refrigerant within a non-hermetic system.

10.7.4 Adsorption systems

Water/zeolite adsorption air conditioning utilises two separate desiccant containers ("beds"), which alternately adsorb (heat release) and desorb (heat required) water vapour which serves to pump water vapour around the system through a condenser and evaporator. The driving force for this type of system is heat; specifically, the heat required for the desorption process. The efficiency of such a system was calculated assuming waste heat utilisation from the engine exhaust stream. Such an assumption is unduly optimistic in that, despite numerous previous attempts to extract waste heat to supplement passenger compartment heating and/or to drive A/C systems, no practical means has been found to do so. Factors reducing the likelihood of waste heat utilisation today are more efficient engines that inherently reject less heat, the inability to use such heat before the catalytic converter (to meet emission requirements), and overall thermal management of said heat, i.e., additional heat exchanger(s), conduits and controls to capture, transport and reject this energy. In fact, this type of system was discussed during recent hearings of the Enquete Kommission (for protection of mankind and the environment) of the Deutscher Bundestag. German Car manufacturers reported that there is no surplus of energy available to drive such a system during idling, city traffic and below cruising speeds of 60 km/h. Diesel engines are not able under any condition to provide such waste energy. In addition, system weight would be twice that, and system volume three times that, of current MAC systems. Added weight would, of course, reduce vehicle fuel efficiency. Zeolite/water systems appear to have limited potential, possibly for some trucks and buses /Wie93/.

10.7.5 Air cycle systems

Air cycle refrigeration has received attention as a possible alternative refrigeration cycle. Air cycle refrigeration uses the expansion of compressed air to provide cooling and currently finds use on aircraft where a source of compressed air is readily available from the turbine engines. Delivering acceptable cooling with reasonable energy efficiency for use in mobile air conditioning would require the development of a high speed, highly efficient turbo-compressor/expander unit coupled with other high efficiency components, such as a high performance heat exchanger to cool the compressed air prior to expansion. Also of critical importance is the dramatic drop in system efficiency accompanying changes in compressor speed. Because of this, an energy efficient means must be devised to control, or modulate, the system when full cooling is not required.

10.7.6 Future mobile A/C systems

It should not be interpreted from the foregoing comments that alternate cycles cannot someday be engineered to render them useful; only that these technologies are currently in their infancy and face significant technical hurdles which must be overcome before they can be considered to be commercialisable.

10.8 Conclusions and recommendations

CFC-12 shortages are expected to force costly retrofitting and/or obsolescence on a large scale in some developed countries, especially in North America. To address this need, retrofit technology is currently being developed and implemented in the affected countries.

10.8.1 Service technology transfer

With respect to transferring retrofit technology to developing countries, a "walk before you run" approach is recommended. It must be recognised that, in general, MAC system service training needs are quite high in these countries for all types of MAC service, especially basic A/C maintenance and repair. While technicians in developed countries are trained and have information available to them to service MAC systems, studies in developing countries (UNEP Multilateral Fund, U.S. EPA MACs Demonstration Projects)) indicate that technicians in developing countries are not as well trained and may even be less knowledgeable than technicians servicing refrigeration equipment used in other sectors within these countries. The value of proper servicing cannot be over-emphasised. The "gas-and-go" type of service, wherein leaks are not repaired and refrigerant is vented directly to the atmosphere during service, must be eliminated. Technicians that repair MAC systems should be technically qualified in basic diagnostic and servicing procedures. All major vehicle manufacturers provide technical information covering such service and international documents such as SAE and ISO address the issue of recycling equipment and associated technician service practices. Local language translation of this information is, of course, essential prior to delivery to technicians. An understanding of proper service techniques would provide the basis for fixing leaky systems and implementing refrigerant recycling and retrofit technology. Of equal importance, a sound understanding of MAC system service would facilitate establishing an infrastructure to promote the sale of HFC-134a vehicles instead of those using CFC-12. The Society of Automotive Engineers (SAE), in co-operation with the mobile air conditioning industry and the U.S. Environmental Protection Agency, has developed technical documents covering equipment requirements for containment and recycling of refrigerants used in mobile A/C systems. SAE documents also include technician service and retrofit procedures that can provide guidance for Article 5(1) countries. Some of these SAE documents have been submitted to ISO/TC22/WG8 for consideration. Without proper technician training and equipment availability, CFC consumption can not be minimised during mobile A/C system servicing.

10.8.2 Retrofitting in Article 5(1) countries

Retrofitting can, and should, be utilised as needed in developed countries. Such retrofitting would help mitigate the effects of CFC phase-out and provide confidence that retrofit procedures are sound and transferable to developing countries. Retrofitting in developing countries is more problematic and, if it occurs at all, should follow establishment of the service infrastructure noted above. It should be noted that virtually every vehicle OEM has stated that CFC-12 systems were designed for CFC-12, work best with CFC-12, and should continue to use CFC-12 as long as possible to ensure expected performance and durability.

In addition to improved service capability, retrofit technology development and implementation, refrigerant recycling should continue to be encouraged on a global scale.

With respect to novel refrigerants and novel refrigerating cycles, although much work is in progress, none have yet been developed that are capable of replacing today's vapour compression HFC-134a systems for mobile air conditioning (section 10.7).

10.9 Summary

10.9.1 World fleet size

Approximately 288 million vehicles with CFC-12 MAC systems are in existence today. The global distribution of these vehicles is estimated to be as follows: 84% (241 million) in the developed countries, 50% (142 million) in the U.S., and 15% (43 million) in the developing countries.

10.9.2 Refrigerant supplies

Refrigerant availability in any given use sector is difficult to forecast. Historically, the mobile air conditioning service industry has required an significant amount of refrigerant, and will continue to require it until the fleet is retrofitted or no longer in service. The phasing out of production of CFCs will likely find service industries competing for the same limited supply of CFC-12. These vehicles have historically required new CFC-12 for service at a rate of approximately 0.40 kg per year per vehicle-on-the-road which can be reduced to 0.19 Kg with global refrigerant recycling.

10.9.3 Industry direction

The accelerated phase-out of CFCs has brought about a corresponding acceleration in the introduction of HFC-134a in new vehicles to the extent that full conversion in Developed Countries was completed during 1994. OEM vehicle manufacturers unanimously selected HFC-134a as their recommended retrofit refrigerant, although other candidate refrigerants may exist and find use in the global marketplace. Activities are currently underway to develop cost-effective and reliable retrofit procedures using HFC-134a in advance of CFC-12 shortages. MAC system manufacturers and component suppliers are expected to provide retrofit information and components to the service industry in a timely manner.

10.9.4 Retrofit concerns

Developing cost-effective and timely retrofit technology is a formidable task. Current MAC systems using CFC-12 were specifically designed for use with CFC-12 and its lubricant, mineral oil. Unique lubricant properties are required that are system and compressor specific to retrofit MAC systems and the task is to identify and develop lubricants that specifically address the needs of each compressor design. Because retrofitting places greater demands on the system (e.g. higher operating pressures), the useful life of system components not changed during retrofit may be shortened. This places both the consumer and the retrofitter at risk of secondary failure and unexpected additional costs.

10.9.5 Retrofit cost

Developing cost-effective and timely retrofit technology is a formidable task. A least-cost incremental retrofit is estimated to be US $ 78. Higher cost scenarios, involving additional component replacements and/or additions are likely to be necessary for a significant percentage of vehicles to maintain acceptable durability and/or performance. It should be emphasised that these costs are exclusive of, and in addition to, the cost of repairing the problems that originally brought the system in for service. These repairs are estimated to average US $ 260 /MAC93/.

10.9.6 Technology transfer

The value of proper servicing cannot be over-emphasised. The "gas-and-go" type of service, wherein leaks are not repaired and refrigerant is vented directly to the atmosphere during service, must be eliminated. Technicians that repair MAC systems should be technically qualified in basic diagnostic and servicing procedures.

The Society of Automotive Engineers (SAE) has developed technical documents covering equipment requirements for containment and recycling refrigerants used in mobile A/C systems. SAE documents also include technician service and retrofit procedures that can provide guidance for Article V countries.

10.9.7 Future systems

AFEAS and the U.S. Department of Energy are currently collaborating on evaluating the technology status and energy usage of selected alternatives. Topics under review are

carbon dioxide, zeolite/water, ammonia, HFCs, air cycle, Stirling cycle. These technologies are currently in their infancy and face significant technical hurdles which must be overcome before they can be considered to be commercialisable.

References

(DuPont, 1988) DuPont assessment of total refrigerant usage by the Mobile A/C industry

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/AFE91/ "Energy and Global Warming Impacts of CFC Alternative Technologies", Fischer, S.K., et al, Oak Ridge National Laboratory, and Kusik, C.L., et al, Arthur D. Little, Inc. Sponsored by the Alternative Fluorocarbons Environmental Acceptability Study and U.S. Department of Energy, (Dec. 1991)

/Bre93/ Proceedings of the 1993 Refrigeration and Air Conditioning Technology Workshop, Breckenridge, Colorado, USA, Dr. Horst Kruse (University of Hannover, Germany, June 23-25, 1993)

/Wie93/ Proceedings of the 1993 Non-Fluorocarbon Insulation, Refrigeration and Air Conditioning Technology Workshop, Wiesbaden, Germany, Dr. Horst Kruse (University of Hannover, Germany, September 27-29, 1993)

/Non94/ Correspondence from Dr. M. Nonnenmann, reviewing author of this section.

Appendix

April 4, 1994

SUBJECT: Summary Society of Automotive Engineers (SAE) documents relating to mobile air conditioning systems.

FROM: Ward Atkinson, Chairman SAE Interior Climate Control Standard Committee

SAE DOCUMENTS

Since the first SAE document J513 in January 1936, which conforms to ANSI B70-1974, SAE refrigeration flare fittings have been an industry standard. In April, 1953, SAE J639 provided standards for system service access fittings currently used by the automotive and commercial industry.

To prevent mis-connections, SAE J639 was revised in the 70's to provide different size system service connections on CFC-12 mobile A/C systems. The use of different high and low refrigeration service access fittings are not used by the commercial industry.

When the mobile industry changed refrigerants from CFC-12 to HFC-134a new unique quick couple service fittings were developed to reduce venting and possible mixing of refrigerants during service of mobile A/C systems.

The mobile air conditioning industry established replacement refrigerant criteria, resulting in new SAE documents.

The industry/EPA field study of mobile A/C systems identified what level of contamination could be expected from used CFC-12 refrigerant and established equipment requirements and the purity levels for recycled refrigerant.

Based on that study, SAE and industry have identified that only refrigerant removed from a mobile A/C, recycled on-site and directly used in a mobile A/C system can be accepted. All used refrigerant from other sources must be sent off-site for processing and must meet the specific ARI recycled purity specification.

ISO ACTIVITY

Documents identified [ISO] have been submitted to the ISO/TC22/ WG8 for consideration as possible future ISO documents.

SUMMARY OF SAE DOCUMENTS

At the request of EPA, SAE Interior Climate Control Standards Committee established working groups to address the needs of the auto industry regarding these environmental concerns. This summary includes SAE documents that have been developed to cover emission, contamination and handling of refrigerants used in the mobile air conditioning industry.

Service Activities

SAE J639 "Safety and Containment of Refrigerant for Mechanical Vapour Compression Systems used for Mobile Air Conditioning Systems"
This document covers system access service fittings, pressure relief valves and system label requirements.

[ISO] SAE J1629 "Cautionary Statements for Handling HFC-134a During Mobile Air Conditioning Service" are identified in this document.
Avoid breathing air conditioning refrigerant and lubricant vapour or mist. Exposure may irritate eyes, nose, and throat.

Do not pressure test or leak test HFC-134a service equipment and/or vehicle air conditioning systems with compressed air.

SAE J2196 "Service Hose for Automotive Air Conditioning"
This defines service equipment (gauge lines) hose emission rates and hose construction requirements.

SAE J2197 "HFC-134a Service Hose Fittings for Automotive Air Conditioning Service Equipment"
To prevent mixing of HFC-134a, with other refrigerants, a new 1/2 inch Acme thread fitting for containers was developed by the "Compressed Gas Association". (CGA) This 1/2 inch Acme thread is also required on HFC-134a automotive service equipment.

Technician Service Procedures

[ISO] SAE J1628 "Technician Procedure for Using Electronic Refrigerant Leak Detectors for Service of Mobile Air Conditioning Systems"
This document provides guidelines for the technician when using an electronic leak detector in determining a system refrigerant leak.

[ISO] DIS 13191 SAE J1989 "Recommended Service Procedure for Containment of CFC-12"
This document covers the technician refrigerant recovery procedure when servicing CFC-12 mobile A/C systems and identification of excess NCGs.

SAE J2211 "Recommended Service Procedure for Containment of HFC-134a"
This document covers the technician refrigerant recovery procedure when servicing HFC-134a mobile A/C systems and identification of excess NCGs.

Service Equipment

[ISO] SAE J1627 "Rating Criteria for Electronic Leak Detectors"
This document establishes the criteria for electronic leak detectors to identify refrigerant leaks.

[ISO] DIS 13192 SAE J1990 "Extraction and Recycle Equipment for Mobile Automotive Air Conditioning Systems"
This covers equipment certification for recycling CFC-12 to meet the standard of purity.

[ISO] DIS 13193 SAE J1991 "Standard of Purity for use in Mobile Air Conditioning Systems"
This identifies the purity level of recycled CFC-12 refrigerant after a contaminated sample has been processed in SAE J1990.

SAE J2209 "CFC-12 Extraction Equipment for Mobile Air Conditioning Systems"
This covers equipment certification for removal of CFC-12 from mobile A/C systems that shall be sent off-site for process to meet ARI 700-88 purity level.

SAE J2210 "HFC-134a Recycling Equipment for Mobile Air Conditioning Systems"
This covers equipment certification for recycling of HFC-134a to meet the standard of purity.

SAE J2099 "Standard of Purity for Recycled HFC-134a for use in Mobile Air Conditioning Systems"
This identifies the purity level of recycled refrigerant after a contaminated sample has been processed in SAE J2210.

The Mobile Air Conditioning industry has established performance certification requirements for recycle and extraction equipment and purity requirements for recycle equipment. Use of certified ARI-740 equipment, which does not have purity standards requirements, can not be used in the mobile air conditioning industry since it does not comply with SAE or Section 609 of The Clean Air Act requirements.

System Components

SAE J51 "Automotive Air Conditioning Hose
This document covers emission rates for CFC-12 refrigerant hoses use on mobile air conditioning systems.

SAE J2064 "HFC-134a Refrigerant Automotive Air Conditioning Hose"
This document covers emission rates and coupling integrity for HFC-134a refrigerant hoses used on mobile A/C systems.

Retrofit Documents

Six new documents were developed at the request of EPA to identify alternate refrigerants and retrofit procedures for conversion of CFC-12 mobile air conditioning systems.

[ISO] SAE J1657 "Selection Criteria for Retrofit Refrigerants to Replace CFC-12 in Mobile Air Conditioning Systems"
This includes flammability, ozone depletion, toxicity and other refrigerant and lubricant compatibility requirements to be usable in mobile A/C systems.

[ISO] SAE J1658 "Alternate Refrigerant Consistency Criteria for Use in Mobile Air Conditioning Systems.
Blend refrigerants consist of more than one substance, this document identifies the proper handling procedure, vapour or liquid phase, and identifies when the remaining container contents can not be used due to improper blend consistency.

[ISO] SAE J1659 "Vehicle Testing Requirements for Replacement Refrigerants for use in CFC-12 Mobile Air Conditioning Systems"
This requires certain vehicle tests which must be conducted to establish any system performance changes due to the alternate refrigerant.

[ISO] SAE J1660 "Fittings and Labels for Retrofit or CFC-12 Mobile Air Conditioning Systems to HFC-134a"
This document covers modification of service fittings and labels for retrofitted vehicles in preventing future system damage and contamination of the refrigerant supplies.

[ISO] SAE J1661 "Procedure for Retrofitting CFC-12 Mobile Air Conditioning Systems to HFC-134a"
This covers the retrofit modification and system processing procedure to reduce the remaining system CFC-12 residue to less than 2%, which is required to reduce future contamination of the HFC-134a refrigerant supply when the vehicle is serviced.

[ISO] SAE J1662 "Material Compatibility With Alternate Refrigerants"
Seals, hoses and "O" rings used in CFC-12 systems may not be compatible with some alternate refrigerants and could break down causing system failures. This document covers test procedures for establishing material compatibility.

Figure 10.1 *Wholesale refrigerant cost/kg U.S.$*

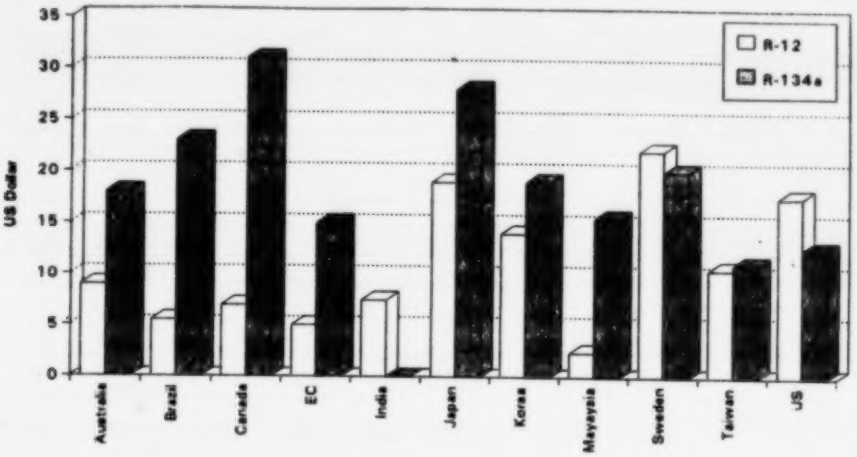

Figure 10.2 *Consumer refrigerant price/kg U.S.$*

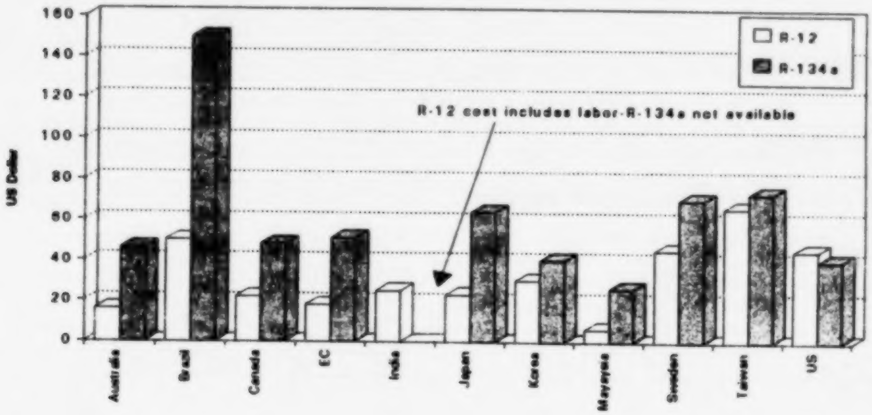

Figure 10.3 *Developed countries A/C vehicles CFC-12 retrofit/obsolescence.*

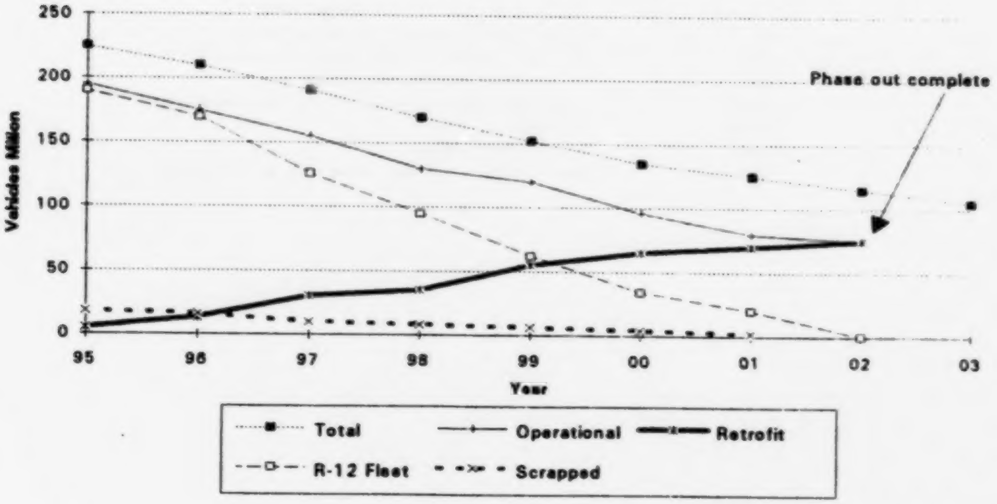

Table 10.1 Global survey summary

Country	AUSTRALIA	BRAZIL	CANADA	EC	INDIA	JAPAN	KOREA	MALAYSIA	SWEDEN	TAIWAN	U.S.
RECYCLING											
Government Require Recycling R12											
YES		1996	X	X		X	X	X	X	X	X
NO	X	X			X						
National R134a Recycle Program											
YES		1996	X	X			X	X	X	X	X
NO	X	X			X	X					
REFRIGERANT SUPPLY/COST											
R12 Produced in Country											
YES	X	X		X	X	X	X			X	X
NO			X					X	X		
R134a Produced in Country											
YES				X		X	1995				X
NO	X	X	X		X			X	X	X	
Repair Facility Cost/Kg U.S. $											
R12	$9.52	$5.34	$7.50	$5.00	$8.00	$19.20	$14.60	$2.59	$22.00	$10.40	$17.60
R134a	$19.04	$23.00	$30.75	$15.00	A	$28.80	$19.50	$15.54	$20.00	$11.10	$12.76
Consumer Price/Kg U.S. $											
R12	$15.18	$50.00	$21.75	$18.00	$25.00 B	$24.00	$30.50	$5.55	$45.00	$66.70	$44.00
R134a	$45.87	$150.00	$47.25	$50.00	A	$66.00	$40.20	$25.90	$70.00	$74.10	$39.60
VEHICLES IN CURRENT SERVICE			X1000								
R12	2800	950	10385	10300	650	46400	4800	1900		3720	141000
R134a	15		100	700		2900	4	0.2		20	3000
USED IMPORTED VEHICLES/YR			X1000								
R12	3				5		0.2			800	
R134a										10	
SERVICE LOCATIONS											
Number of Locations	7500	200		10000	20000	70000	35000	2500		1500	100000
ESTIMATED R12 VEHICLES IN FUTURE SERVICE					X1000						
YEAR											
1995	2340	40		10100	974	7000	5000		250	3400	100944
1996	2000	38		9300	1174	6000	4500		300	3000	91645
1997	1820	35		8300	1404	5000	4000		250	2600	82262
1998	1560	25		7450	1688	4000	3300		200	2200	72761
1999	1300	22.5		6250	1725	3000	3000		150	1800	63550
2000	1040	20		4850	1960	2000	2300		100	1400	54751

W.Atkinson July 30, 1994 mpf1

NOTES:

A: R134a not commercially available

B: Includes labor charge

GLOBAL SURVEY CONTRIBUTORS

Australia	J. Phillips, Air International
Brazil	Gijo Kikuti, Nippondenso
Canada	R.S. St.Lewis, Environment Canada
European Countries	Dr. M. Nonnenmann, Behr C. Petitjean, Valeo
India	Dr. R.S. Agarwal, Institute of Technology, Delhi
Japan	M. Shimizu, Calsonic N. Kato, Zexel R. Muraoka, JAPIA
Korea	E.T. Kim, Korea Auto Maunfacturers
Malaysia	I. Ithini, Department of Environment H. E. Kwi, Nippondenso
Sweden	Per Henriksson, Volvo
Taiwan	S.S. Liu, Taiwan Calsonic
United States	Ward J. Atkinson, Sun Test James A. Baker, Harrison,GMC

Table 10.2 *Least-cost HFC-134a retrofits*

Service Operation:	**System Type:** Orifice Tube		**System Type:** Expansion Valve	
	Parts (U.S.$)	**Labor** (Hours)	**Parts** (U.S.$)	**Labor** (Hours)
Evacuation to Remove Residual CFC-12		0.65		0.65
High Pressure Cut-Out Device	$30.00	0.3	$30.00	0.3
Fittings and Label (s)	$15.00	0.5	$15.00	0.5
Lubricant	$5.00		$5.00	
Total Parts Cost	$50.00		$50.00	
Total Labor Cost (US$ 50/Hr.)		$72.50		$72.50
Total Cost US$		$122.50		$122.50

LEAST-COST RETROFIT US$ 122.50

Table 10.3 Refrigerant requirements for MACs in developed countries (kt)

Year	1995	1996	1997	1998	1999	2000	2005
CFC-12 REQUIREMENTS							
CFC-12 Service							
Vehicles (Millions)	224	206	189	169	152	135	74
New CFC-12	42.5	39.3	36.1	32.2	28.8	25.6	14.1

Quanties listed for 1996 and beyond represent shortages of new CFC-12.

These shortages force retrofit/obsolescence.

Year	1995	1996	1997	1998	1999	2000	2005
HFC-134a REQUIREMENTS							
HFC-134a OEM (New vehicle production)							
Vehicles (Millions)	22.7	23.3	24	24.8	25.5	26.3	30.5
New HFC-134a	24.9	25.7	26.4	27.2	28	28.8	33.4
HFC-134a Retrofit							
Vehicles (Millions)	4.7	8.6	13.2	13	9	6.4	0
New HFC-134a	5.2	9.5	14.5	14.3	9.9	7	0
HFC-134a Service							
Vehicles (Millions)	54.8	86.7	124	162	197	230	259
HFC-134a use rate (Kg/veh/yr)	0.08	0.09	0.1	0.11	0.12	0.13	0.16
New HFC-134a	4.4	7.8	12.4	17.8	23.6	29.9	41.4

Total HFC-134a Required (Million Kg)

Year	1995	1996	1997	1998	1999	2000	2005
	34.5	43	53.3	59.3	61.5	65.7	74.8

8-1-94

Table 10.4 U.S. retrofit scenario

	CFC-12	Retrofit &	CFC-12	CFC-12	CFC-12	Inventory	CFC-12	CFC-12	CFC-12	CFC-12	CFC-12	CFC-12
	Retrofit	Obsoleted	Vehicles	Vehicles	Vehicles	at start of	Need	New	Need-new	Need	Vehicles	from
Year	Vehicles	Prior Year	Existing	Operating	Operating	Year		Vehicles	Vehicles	Total	Scrapped	Scrap
Algorithms		3+16+21+24	2-3		4 x 5		6 x 0.19		9 x 1.18	8+10		12 x 0.22
1	2	3	4	5	6	7	8	9	10	11	12	13
	(millions	(millions)	(millions		(millions)	(mt)	(mt)	(millions)	(mt)	(mt)	(millions)	(mt)
1995	132	3	129	87%	112	15,800	21,263	0	0	21,263	10	2,162
1996	122	6	116	84%	97	10,060	18,515	0	0	18,515	10	2,227
1997	112	11	100	81%	81	3,353	15,466	0	0	15,466	11	2,519
1998	100	20	81	78%	63	0	11,955	0	0	11,955	11	2,407
1999	89	28	61	75%	46	0	8,746	0	0	8,746	10	2,186
2000	80	34	46	72%	33	0	6,252	0	0	6,252	7	1,592
2001	72	38	34	69%	24	0	4,509	0	0	4,509	7	1,492
2002	66	41	25	66%	16	0	3,132	0	0	3,132	6	1,365
2003	59	42	17	63%	11	0	2,062	0	0	2,062	7	1,490
2004	53	43	10	60%	6	0	1,136	0	0	1,136	9	1,939

	Voluntary	Voluntary	CFC-12	CFC-12	Vehicles	%	Vehicles	CFC-12	Final	Forced	Inventory	TOTAL
	Retrofit	Retrofit	from	Shortfall	Retrofit or	Obsoleted	Obsoleted	from	Shortfall	Retrofits	at	Retrofits
Year			Vol. Retr		Obsoleted			Obs. Veh.			End	
Algorithms		6 x 15	16 x 1.18	11-13-7-17	18/1.18		19 x 20	21x1.18x0.	18-22	23/1.18		16 24
14	15	16	17	18	19	20	21	22	23	24	25	26
		(millions)	(mt)	(mt)	(millions)		(millions)	(mt)	(mt)	(millions)	(millions)	(millions)
1995	2.50%	2.8	3,301	0	0	10%	0	0	0	0	10,060	2.8
1996	2.50%	2.4	2,875	3,352	2.8	10%	0.3	201	3,151	2.7	3.353	5.1
1997	2.50%	2	2,401	7,193	6.1	10%	0.6	432	6,761	5.7	0	7.8
1998	2.50%	1.6	1,856	7,692	6.5	10%	0.7	462	7,230	6.1	0	7.7
1999	2.50%	1.2	1,358	5,202	4.4	10%	0.4	312	4,890	4.4	0	5.3
2000	2.50%	0.8	971	3,690	3.1	10%	0.3	221	3,468	2.9	0	3.8
2001	2.50%	0.6	700	2,316	2	10%	0.2	139	2,177	1.8	0	2.4
2002	2.50%	0.4	486	1,231	1.1	10%	0.1	77	1,204	1.1	0	1.4
2003	2.50%	0.3	320	253	0.2	10%	0.1	15	238	0.2	0	0.5
2004	2.50%	0.1	176	0	0	10%	0	0	0	0	0	0.1

Total = 36.9

Assumptions: 0.19 kg/veh serviced , 0.22 kg/veh scrapped   MY Phase-in 5%('92), 15%('93), 95%('94), 100%('95)   1994-5 Production = 41,000 mt/yr

8 1 94

11 Heat pumps (heating only and heat recovery)

11.1 Introduction

Energy conservation is one of the main strategies to meet the environmental problems arising from the continuously growing energy demand world-wide. Heat pumps, which today are a proven, reliable, cost-effective and energy saving technology, utilise environmental and waste heat and consequently reduce the demand for fossil fuels for heating, cooling and dehumidification in residential/commercial buildings and industrial applications. Because heat pumps require less primary energy than conventional heating systems, they are considered an important technology for reducing emissions of gases that harm the environment, such as carbon dioxide (CO_2), sulphur dioxide (SO_2) and nitrogen oxides (NO_x).

The vast majority of heat pumps currently in operation are electrically driven closed-cycle compression type systems. The overall environmental impact of electric heat pumps depends to a large extent on how electricity is generated. Furthermore, most refrigerants currently used in heat pumps are CFCs and HCFCs, substances now held to contribute to both the depletion of the earth's ozone layer (ODP) and the greenhouse effect (GWP). Hence, loss of these refrigerants during operation, maintenance and scrapping will partly counteract the reduction in specific CO_2 emissions.

The Total Equivalent Warming Impact (TEWI) combines the global warming effect associated with energy consumption, i.e. the specific CO_2 emissions from electricity generation (indirect GWP) and with refrigerant leakage's (direct GWP). The TEWI concept is useful to indicate the relative contribution to future global warming. The TEWI depends amongst others on how electricity is generated (hydro power, renewables, nuclear or coal/oil/gas-fired power stations), the Seasonal Performance Factor of the heat pump (SPF), the GWP of the refrigerant, the lifetime of the system and the leakage rate.

Section 11 discusses working fluids for heating-only and heat recovery heat pumps. Reversible air conditioners, which comprise virtually all heat pump installations in the United States, Japan and other countries with a considerable cooling demand, are presented in .section 7, "Air Conditioning & Heat Pumps (Air-Cooled Systems)".

11.2 Current status

11.2.1 Types and volume of equipment

Heating-only heat pumps are used for space and water heating in residential, commercial/institutional and industrial buildings. In industry heat pumps are used for heating of process streams, heat recovery and hot water/steam production. They are also an integrated part of industrial processes, such as drying, evaporative concentration and distillation.

Space heating heat pumps in residential and commercial/institutional buildings typically operate between 1,000 to 5,000 hours a year, depending on the climatic conditions, type and purpose of the building, etc. Industrial heat pumps have much longer operating hours, typically between 6,000 to 8,000 hours. The majority of industrial heat pumps operate in the chemical and food processing industries.

11.2.1.1 Residential and commercial/institutional applications

Heating-only heat pumps in buildings are manufactured in all sizes ranging from 1 kW heating capacity for single room units, to 50-1,000 kW for commercial/institutional applications, and tens of MWs for district heating plants. Most small to medium size heat pumps in buildings are standardised, factory made units. Large heat pump installations are usually custom made and partly or totally assembled at the site. Hot water heat pumps have captured a small fraction of water heater sales in the OECD countries. Commercial applications are more attractive relative to competitive systems than residential applications. Approximately 500,000 units are currently installed in Europe /HPC93/.

Heat sources include ambient and ventilation air, sea and lake water, sewage water, ground water, soil, rock and industrial waste water and effluent. Air and ground source heat pumps dominate the market. Evaporation temperatures typically range from -10°C to +10°C, with condensation between 40°C and 80°C, depending on the type of heat sink. Air is the most common distribution medium, except in most of the European countries and Northern parts of North America where hydronic (water) systems are predominant. The majority of heating-only heat pumps currently in operation are electric closed-cycle compression type units, using a CFC or HCFC refrigerant. The number of engine driven systems is small but growing. Advanced gas-fired absorption heat pumps have been introduced into the market recently. The market share is negligible compared to vapour compression systems.

The vast majority of heating-only heat pumps in residential and commercial/institutional buildings are located in Western Europe. It is estimated that the total number of heating-only heat pumps in these market sectors (including district heating) is roughly 1.4 million units, with a total heating capacity of about 11,000 MW and an annual heat supply of 25 TWh/year /HPC94, Gil93/. Refrigerant charges range between 0.1 and 1.5 kg per kW thermal output, with 1.0 kg/kW as an estimated average /Tor91/. The current trend is towards compact heat pumps with small refrigerant charge.

11.2.1.2 Industrial applications

Industrial heat pumps are generally large in thermal capacity ranging from about 100 kW to several MWs, and the systems are often custom designed. Evaporation temperatures are generally higher than with residential and commercial/institutional applications and condensation temperatures are typically in the 80°C to 150°C range. Industrial heat pumps have a much higher coefficient of performance (COP) than space heating heat pumps. This is mainly due to the small temperature lifts, large size, efficient design and stable operating conditions.

The type of heat pump applied depends heavily on the process, the heat source and the operating temperatures. The most common types of industrial heat pumps are:

- Mechanical vapour recompression (MVR) systems, or open (semi-open) heat pumps, are extensively used in industrial processes where liquid is evaporated. Most systems operate with water vapour as the working fluid. In chemical industry other process vapours are used in MVRs (e.g. acetone, methanol).

- Electric closed-cycle compression heat pumps are the most commonly used type of heat pumps world-wide, but also a growing number of engine driven systems are installed. Traditionally, these heat pumps have been using CFCs or HCFCs, but in recent years ammonia, HFCs and propane have been introduced. These working fluids are used yet on a small scale. Refrigerant charges in industrial closed cycle heat pumps range from 0.5 to 2.5 kg per kW thermal output, with an estimated average charge roughly the same as for residential and commercial/institutional heat pumps, i.e. 1.0 kg/kW /Tor91/.

- Absorption heat pumps (section 11.4.6.1) are to a small extent installed in industrial applications and in refuse incineration plants to recover heat from the flue gas cleaning process. The capacity of these installations range from 5 to several ten's of MW. Most absorption heat pumps use water and lithium bromide as the working pair, and are capable to deliver heat up to 100°C.

- Heat transformers (section 11.4.6.2) are used to produce useful high-temperature heat from medium-temperature industrial waste heat. Current systems use water and lithium bromide as the working pair. The maximum delivery temperature is 150°C.

The total number of industrial heat pumps world-wide is estimated at 7,000 units, with a total heating capacity of about 2,500 MW and a heat production of 12 TWh/year /HPC94, Gil93/.

11.2.2 Refrigerants

Traditionally the most common refrigerants for closed cycle compression heat pumps have been (figures in brackets indicate share of refrigerant consumption in 1990) /Cat94/:

- CFC-12 (46%)
- HCFC-22 (41%)
- R-502 (8%)
- CFC-11 (4% - heat recovery from centrifugal chillers)
- CFC-114 (1%)
- R-500 (<1%)

Refrigerants in heat pumps are primarily chosen in accordance with the temperature level of the heat sink and heat source. A typical application pattern for traditional refrigerants is given in Table 11.1.

Table 11.1 ***Typical application pattern of traditional refrigerants in heating-only heat pumps.***

Heat Sink Temperature		
Below 55°C	**55-80°C**	**Up to 125°C**
HCFC-22 R-502	CFC-12 R-500	CFC-114

The consumption of CFCs (mainly CFC-12) and HCFCs (mainly HCFC-22) in heating-only heat pumps in 1993 is indicated in Table 11.2. These figures include charging of new heat pumps as well as recharging and retrofitting of existing installations. The data are extrapolated from the 1990 statistics /Tor91/, and later developments. The table also gives an estimate of the total refrigerant volume in existing heat pump installations in 1993. Due to many uncertainties in the calculations, all data are to be regarded indicative.

Table 11.2 ***Estimated annual consumption and total volume of CFCs and HCFCs in heating-only heat pumps (1993). No statistics are available for HFC-134a, ammonia and other replacement refrigerants.***

Refrigerants	**Consumption, 1993 [tonnes/year]**	**Total Volume, 1993 [tonnes]**
CFCs	1,000	6,500
HCFCs	800	4,500

Several European countries have banned the use of CFCs in new heat pump installations since 1992, consequently increasing the consumption of HCFC-22, HFC-134a and other refrigerants. Recently, ammonia has attained a growing market share as a refrigerant in large capacity heat pump systems in Europe, while there is an increase in the use of propane in projects involving small systems, in Europe as well.

11.3 Existing heat pump installations

11.3.1 General

Heat pump systems have an average lifetime expectancy of 15-25 years. A large number of existing installations using CFCs and HCFCs are expected to operate beyond the date of CFC and HCFC phaseout. Hence, measures have to be taken to ensure full life time operation. In practice, two options are available. Refrigerants can be *recovered/reused* or heat pumps can be *retrofitted* with alternative refrigerants.

11.3.2 Reuse and recovery of refrigerants

It will neither be technically feasible, nor economically justifiable to retrofit or dismantle all heating-only heat pumps using CFCs by 1995/96. Hence, reuse or recovery of refrigerants will, in the short-run, play an important role. Provided that a proper quality of recovered refrigerants is secured, existing heat pumps may be allowed to continue operating with the refrigerant they have been designed for. Main challenges will be to seal leakage's and repair existing equipment, and to ensure high quality standards for the recycling process. An important aspect in this matter will be the *availability* of high quality recovered refrigerants for service purposes. Assuming 60% "recovery efficiency", about 2,300 tonnes of CFCs will be made available from heat pumps for reuse between 1995 and 2000, which is about 20% more than is actually needed for servicing existing installations using CFCs (section 11.6).

11.3.3 Retrofitting

The degree of plant modification depends on factors such as the alternative refrigerant chosen, system design, size, etc. Old, leaking installations in poor technical condition should preferably be scrapped and replaced with new equipment. Relatively new heat pump systems must be sealed before any retrofitting is carried out. Technically, most equipment can be retrofitted with new refrigerants. In general retrofitting involves a thorough and systematic evaluation of safety, reliability, capacity requirements and energy efficiency. Other aspects, such as equipment, refrigerant and labour costs, as well as availability of refrigerants are taken into consideration when selecting retrofit refrigerants. Typical modifications include change of lubricant, adjustment or change of expansion device, change of desiccant material, replacement of non-compatible sealing materials (elastomers in O-rings, gaskets, etc.), and compressor modifications/replacement. For details on retrofitting procedures for heat pumps using CFC-11, CFC-12, R-500, R-502 and HCFC-22 reference is made to /Cat94/.

Table 11.3 provides an overview of today's refrigerant alternatives for retrofitting heat pumps.

Table 11.3 Alternatives for retrofitting of heating-only heat pumps

Refrigerant	Alternative Refrigerants for retrofitting	
	Short Term	**Medium/Long Term**
CFC-11	• HCFC-123	• HCFC-123
CFC-12 and R-500	• Blends containing HCFCs	• HFC-134a • propane • HFC-152a
CFC-114	• HCFC-124 • HCFC-123	
R-502	• Blends containing HCFCs • HCFC-22	• HFC blends
HCFC-22		• HFC blends • Propane

11.3.3.1 CFC-11 alternatives

Examples of CFC-11 heat pump retrofits are not widely available.

11.3.3.2 CFC-12 and R-500 alternatives

a) HFC-134a

When retrofitting from CFC-12 (or R-500) to HFC-134a, the mineral oil is replaced with a polyolester lubricant. Proper cleaning of the heat pump system is crucial before recharging with HFC-134a, since residual mineral oil, sludge deposits and moisture may cause serious operational problems. Standardised cleaning methods have been developed, and a number of small, medium and large capacity heat pumps have already been successfully retrofitted.

b) Blends

Currently available blends for replacing CFC-12 and R-500 in heat pumps are near-azeotropic, are HCFC-22 based, and only minor system modifications are needed. When alkylbenzene lubricants are used, the cleaning process is much less critical compared to HFC-134a retrofitting. A common ternary blend for retrofitting heat pumps using CFC-12 and R-500 is R-401A, which consists of HCFC-22/HCFC-124/HFC-152a (52/34/13%). Volumetric refrigeration capacity and theoretical energy efficiency is approximately the same as for CFC-12.

c) Propane

CFC-12 and R-500 in heat pumps can be replaced by propane. Depending on the operating conditions, the volumetric refrigeration capacity of propane is 35-50% higher than that of CFC-12. Consequently, compressor/motor modifications are required in order to maintain the same heating capacity. Maximum achievable condensing temperature at 25 bar operating pressure will drop from 83°C to about 68°C when retrofitting from CFC-12 with propane. Due to its flammability propane should only be retrofitted into systems with low refrigerant charge. Adequate safety precautions should be taken (section 11.4.5.2), and systems design and refrigerant charge should, as a general rule, meet regional/national codes and regulations.

d) HFC-152a

HFC-152a can replace CFC-12 and R-500 in existing heat pumps. The volumetric refrigeration capacity is about 5% lower than that of CFC-12, hence no compressor modifications are required. Since HFC-152a and CFC-12/R-500 have similar physical properties and condensation/evaporation temperatures etc. will remain the same. Due to the flammability of HFC-152a, the same safety precautions should be followed as when retrofitting to propane.

11.3.3.3 CFC-114 alternatives

HCFC-124 is a possible alternative for retrofitting heat pumps using CFC-114. HCFC-124 requires higher operation pressure levels than CFC-114, and is in many cases not suitable for retrofitting heat pumps since the pressure levels will exceed design ratings. Moreover, the volumetric refrigeration capacity of HCFC-124 is 40-45% higher than that of CFC-114, and complete compressor and motor replacement is necessary in order to maintain required heating capacity.

11.3.3.4 R-502 alternatives

Current alternatives for retrofitting heat pumps using R-502 include HCFC-22 and blends. The volumetric refrigeration capacity of HCFC-22 is slightly higher than that of R-502, and the system pressure is almost the same. Hence, it is not necessary to replace the compressor when retrofitting from R-502 to HCFC-22, and only minor system modifications are needed. However, high discharge temperatures when operating at high temperature lifts may cause operational problems.

A number of blends containing HCFCs have been developed. Next to the R-401 blends, another near-azeotropic blend is R-402A, which consists of HFC-125/HCFC-22/propane (60/38/2%). The retrofitting procedure is simple and inexpensive. HFC blends for retrofitting heat pumps using R-502 have been commercially available as of 1993/94, including compositions of HFC-32/125/134a, HFC-32/125/143a and HFC-125/143a/-134a. The retrofitting procedure for HFC-blends is similar to HFC-134a retrofitting.

11.3.3.5 HCFC-22 alternatives

Current alternatives for retrofitting heat pumps using HCFC-22 are -project-wise-propane and HFC blends. The volumetric refrigeration capacity of propane is almost the same as with HCFC-22, and no compressor modifications are needed. The maximum achievable condensing temperature when using standard 25 bars equipment increases from about 61°C to 68°C. In Germany a number of heat pumps using HCFC-22 have been successfully converted to propane /Nlj93/. It should be emphasised that dealing with flammability safety features will be required in these retrofits. A number of HFC blends which can replace HCFC-22 and R-502 in existing heat pump installations have been commercially available from 1993/94, including compositions of HFC-32/125/134a, HFC-32/125/143a and HFC-134a/125/143a. The retrofitting procedure for HFC-blends is similar to HFC-134a retrofitting.

11.4 New heat pump installations

11.4.1 General

As a general requirement, heat pumps using refrigerants other than CFCs and HCFCs should have at least the same reliability and be as cost effective as (H)CFC systems. Moreover, the energy efficiency of the new systems should be the same or higher. In addition to developing new and environmentally acceptable refrigerants, it is important to modify or redesign heat pumps in order to achieve these goals. In general, the energy efficiency of a heat pump depends more on the working cycle and system design than on the refrigerant used.

11.4.2 HCFC Refrigerants

Many European countries are discussing regulations on HCFCs with a view to phaseout more rapidly than has already been accepted under the Montreal Protocol. This will influence the scenarios for heat pumps in Europe.

11.4.2.1 HCFC-22

HCFC-22 is currently applied both as a pure refrigerant and as a component in blends replacing CFC-12 and R-502.

11.4.2.2 HCFC-123

HCFC-123 is suggested as a short-term alternative to CFC-114 in high temperature heat pumps (160°C at 25 bar). HCFC-123 has about 30% lower volumetric refrigeration capacity than that of CFC-114 at 100°C evaporation temperature. The major disadvantage with HCFC-123 is its toxicity. Hence, engine rooms for HCFC-123 heat pumps must be equipped with gas detectors, adequate ventilation systems and means to alert operators in the event of significant leakage.

11.4.2.3 HCFC-124

HCFC-124 is currently applied as a component in ternary blends replacing CFC-12. It is also regarded as a short- and medium term alternative to CFC-114 in high-temperature heat pumps. HCFC-124 requires operation at higher pressure levels than CFC-114, and the condensation temperature at 25 bar pressure is limited to 105°C (130°C for CFC-114). The volumetric refrigeration capacity is about 40-45% higher relative to CFC-114.

11.4.2.4 HCFC-141b

HCFC-141b has properties similar to HCFC-123, and can be used as a replacement for CFC-114 in the lower temperature range. HCFC-141b has low toxicity, but is flammable. A blend of HCFC-123 and HCFC-141b has also been proposed /Wfl93/. The aim of this proposition is to diminish the toxicity of HCFC-123 by mixing it with HCFC-141b.

11.4.3 HFC refrigerants

The most interesting HFC refrigerants for heat pump applications are HFC-134a used as a single refrigerant and HFC-152a, HFC-32, HFC-125 and HFC-143a applied as components in blends. All HFCs and HFC blends require polyolester lubricants.

11.4.3.1 HFC-134a

HFC-134a is quite similar to CFC-12 and R-500 in terms of thermodynamic and physical properties, and is regarded as the main successor of CFC-12 in medium temperature heat pump systems. The condensation temperature at 25 bar is approximately 77°C. HFC-134a is used in many new heat pump installations, and initial costs of HFC-134a systems are approximately 10% higher compared to CFC-12 systems.

Above -10°C evaporation temperature, the compressor efficiency and COP of a heat pump system is almost the same as for CFC-12 /Hau93/. Extensive liquid subcooling is recommended to improve system energy efficiency. The volumetric refrigeration capacity of HFC-134a is typically 2-3% lower than with CFC-12 at 0°C evaporation temperature /Hau93/, hence a slightly higher compressor capacity is needed.

11.4.3.2 HFC-152a

HFC-152a has long been considered a promising alternative refrigerant to CFCs due to its favourable thermodynamic and physical properties and low GWP factor. However, a major problem is the availability of the refrigerant in the Western part of the world where virtually all heating only heat pumps are installed. There are, however, many examples of successful HVAC applications with HFC-152a. It has been applied in a certain number of small heat pump systems, domestic refrigerators and in some commercial refrigeration units, mostly on a demonstartion basis, e.g. in the United States, Scandinavia and China /Nil91, Tor91, Cat94/. E.g. in China, some commercial production of HFC-152a refrigerators will start in 1995/96. Heat pumps using HFC-152a have approximately the same COP as CFC-12 systems at the same operating conditions /Ree92/. The volumetric refrigerating capacity of HFC-152a is approximately 5% lower relative to CFC-12 at operating conditions 0°C/40°C /Cat94/. Due to its flammability HFC-152a should only be applied in small heat pump systems with low refrigerant charge. Refrigerant charges up to about 5 kg per unit is considered acceptable /Nil91, Cat94/. When designing new heat pump plants with HFC-152a, adequate safety precautions should be taken to ensure safe operation and maintenance (section 11.4.5.2).

11.4.3.3 HFC-32

HFC-32, which is a moderately flammable refrigerant with a GWP close to zero, is considered a suitable long-term component in non-flammable ternary blends replacing HCFC-22 and R-502 in heat pump, air conditioning and refrigeration systems (section 11.4.4).

11.4.3.4 HFC-125 and HFC-143a

HFC-125 and HFC-143a have properties fairly similar to R-502 and HCFC-22, and are mainly applied as components in ternary blends replacing R-502 and HCFC-22 (section 11.4.4).

11.4.3.5 Other alternatives

HFC-227 is an alternative to CFC-114 in high temperature heat pumps. The theoretical energy efficiency of a heat pump system using HFC-227 is lower than that of CFC-114 /Wfl93/. HFC-245ca and HFC-356 are identified as possible long-term replacements for CFC-114 in high-temperature heat pumps. At present, there is not much information available regarding stability, toxicity and GWP for these refrigerants. In the USA, a number of partially fluorinated propanes plus two- and three-carbon ethers have been synthesised. Eleven of these compounds show potential as substitutes, and their properties suggest that as pure fluids and blends they could be applied for most heat pump applications /Nlm94/. However, most materials are in too limited supply for adequate performance testing and toxicity testing.

11.4.4 Blends

Refrigerant blends represent an important option for replacement of CFC and HCFC refrigerants, both for new heat pump installations and for retrofits.

11.4.4.1 HCFC blends

Most of the blends commercially available contain HCFC-22 and other HCFC refrigerants. All HCFC blends require alkylbenzene or polyolester lubricants.

- Ternary blends containing HCFC-22, HCFC-124 and HFC-152a are currently available alternatives to CFC-12 in heat pumps. A common composition is 53/34/13% (R-401A). The volumetric refrigeration capacity and theoretical energy efficiency is approximately the same as for CFC-12, and the temperature glide is approximately 4°C.
- A binary blend containing HCFC-22 and HCFC-142b is another alternative to CFC-12. The blend is non-flammable, as long as the HCFC-22 content is at least 30% by weight. The temperature glide is approximately 10°C.
- There has been developed a number of blends for replacing R-502 in various applications. Two common compositions are HFC-125/HCFC-22/propane (60/38/2%, R-402A) and HCFC-22/FC-218/propane (55/39/6%, R-403A - which implies a higher GWP).

11.4.4.2 HFC blends

All HFC blends require polyolester lubricants. Various compositions of HFC-125/143a/-134a, HFC-32/125/134a and HFC-32/125/143a are current alternatives to R-502. The United States, Japan and Europe are at present carrying out considerable research efforts in order to find suitable replacements for HCFC-22. In the United States and Japan most attention is given to HFC blends, and the alternatives evaluated includes compositions of /IEA93/:

- HFC-32/125
- HFC-32/134a
- HFC-32/125/134a
- HFC-32/125/propane/134a
- HFC-32/227ea

11.4.5 "Natural refrigerants"

"Natural refrigerants" are long-term alternatives to CFCs and HCFCs in heat pump systems. The most significant and promising refrigerants are ammonia, hydrocarbons (e.g. propane and blends of propane, butane and isobutane), carbon dioxide and water. Annex 22, "Compression Systems with Natural Working Fluids" under the IEA Implementing Agreement on Heat Pumping Technologies (1994-97), will amongst others provide state-of-the-art information on compression heat pumps with natural working fluids, and establish guidelines and safety recommendations for new heat pump installations.

11.4.5.1 Ammonia

Ammonia is gaining popularity in Northern Europe, and has been applied in a number of medium-size and large capacity heat pumps, mainly in Scandinavia and Germany /Nld93, Nlm94, Kru93/. Ammonia heat pumps typically achieve a 3-5% higher energy efficiency than systems using CFC-12, HCFC-22 or HFC-134a /Cat94/. However, in applications where indirect heat distribution systems are required, no net efficiency gain is expected. The volumetric refrigeration capacity is approximately the same as for HCFC-22 and about 40% higher than for CFC-12 and HFC-134a, thus reducing the compressor capacity needed. High pressure (40 bars) piston compressors are commercially available, raising the achievable condensing temperature from 55°C (25 bar) to about 78°C.

Ammonia yields high compressor discharge temperatures, and at high temperature lifts two-stage compression may be necessary to avoid operational problems. Consequently, initial costs will increase by 15-20% and energy efficiency will increase 25-30% /Cat94/. Semi-hermetic ammonia compressors as well as soluble lubricants (polyglycols) have recently been introduced, and hermetic ammonia compressors are expected to be available within a few years. In general, system safety requires that machine rooms are designed according to prevailing standards. Safety design measures can include proper placing and/or gas tight enclosure of the heat pump, application of low-charge systems, use of indirect heat distribution systems (brine systems), fail-safe ventilation systems, gas detectors (alarm system), water spray system, etc. Although ammonia is an excellent high-temperature refrigerant, it has not been applied in industrial heat pumps operating above 80°C. This is mainly due to the lack of high-pressure compressors with a reasonable efficiency. A prototype ammonia heat pump for drying is under development in Norway, operating at a maximum condensing temperature of 100°C /Jon94/.

More detailed information about ammonia applications and properties can be found in section 5.

11.4.5.2 Hydrocarbons

Hydrocarbons (HCs) are flammable long-term, proven refrigerants which have been used in large refrigeration plants for many years, notably in petrochemical industry. Today hydrocarbons emerge as a viable option for replacement of CFCs and HCFCs, amongst others in residential heat pumps. The most important hydrocarbons for medium-temperature heat pump applications are propane (HC-290) and blends of propane and (iso)butane (HC-600a/HC-600). Propylene (HC-1270), which is regarded an alternative to HCFC-22, has recently been studied and tested in Germany. At present, there is no literature information about hydrocarbon replacements for CFC-114 in high-temperature heat pumps /Wfl93/. The volumetric refrigerating capacity of propane is approximately the same as for HCFC-22, and in a practical application propane will yield about the same energy efficiency as CFC-12 /Wfl93/. Maximum condensing temperature with standard 25 bar equipment is about 68°C.

A number of prototype heat pumps with propane are installed /Nld93, NLA94/. From January 1994 water-to-water and air-to-water heat pumps for residences and swimming pools are available from a German manufacturer. A 100 kW swimming pool heat pump using 20 kg of propane has been installed in Germany /Nld93/. Other German and Austrian manufacturers of residential heat pumps have decided to use propane as well. When designing new heat pump systems with propane or other flammable refrigerants, adequate safety precautions should be taken to ensure safe operation and maintenance. Typical safety measures include the addition of tracer gases, a proper placement and/or gas tight enclosure of the heat pump, application of low-charge systems, fail-safe ventilation systems and gas detector activating alarm systems.

11.4.5.3 Carbon dioxide

Carbon dioxide (CO_2) offers a number of advantages. With regard to safety, CO_2 is at least as good as the best of halocarbons due to its non-toxicity and inflammability. CO_2 is compatible to normal lubricants and common machine construction materials. At 0°C the volumetric refrigerating capacity of CO_2 is between five and eight times higher than for other refrigerants, consequently reducing the compressor volume. The pressure ratio is also greatly reduced compared to conventional refrigerants. The relatively low molar mass of CO_2 reduces the mass flow and the required dimensions of compressor, valves and piping. Due to the limited volume of the system, the high pressure (above 100 bar) does not constitute a large danger in the case of rupture.

The theoretical COP of a CO_2 heat pump cycle is rather poor, and the effective application of this fluid depends on the development of suitable methods to achieve a competitively low power consumption near and above the critical point /Lor93/. By adapting the standard compression cycle, high performance can be achieved. A laboratory prototype of a CO_2 car air-conditioner, based on a supercritical high-side pressure has been tested. The results prove that the COP of the CO_2 system is at least as good as the standard CFC-12 system /Car92/. The ability of the transcritical CO_2 process to absorb heat at constant temperature and reject heat at gliding temperature above supercritical pressure, makes it well suited for heat pump applications where natural heat is the heat source and with a considerable temperature glide (30-50°C) on the heat distribution side. Examples of such applications are heat pump water heaters and large heat pumps in district heating systems. The transcritical CO_2 process utilised for water heating has been examined, and the conclusion is that a CO_2 heat pump is capable of reducing the energy consumption as much as 30% compared to standard heat pump water heaters using CFC-12 or HFC-134a /Nek92/. Carbon dioxide is not expected to become of much commercial importance, at least not until the late 1990s.

11.4.5.4 Water

Water is an excellent refrigerant for high-temperature industrial heat pumps due to its favourable thermodynamic properties and the fact that it is neither flammable nor toxic. Water has mainly been applied as a working fluid in open and semi-open MVR systems in industrial evaporation processes. Operating temperatures are in the range 80 to 150°C. A closed-cycle prototype heat pump has reached an output temperature of 300°C (85 bar) /IHP89/. The major disadvantages using water as refrigerant are the low volumetric refrigeration capacity and the relatively high pressure ratio, especially at evaporating temperatures below 100°C.

11.4.6 Alternative technologies

11.4.6.1 Absorption heat pumps (type I)

Absorption heat pumps for space heating are mostly gas-fired, whereas industrial systems are typically driven by steam or waste heat. Most of the systems use water and lithium bromide as the working pair, and can achieve about 100°C output temperature. Industrial absorption heat pumps are, for economic reasons, mainly used in large sizes (MW). Residential absorption heat pumps are still under development. In industry absorption heat pumps are applied on a negligible scale only. In Sweden and Denmark a number of installations are in operation. They recover heat from flue gas cleaning systems in refuse incineration plants or use geothermal heat as heat source (Denmark). Absorption heat pumps with a typical primary energy ratio (PER) in the range of 1.2 to 1.5, have a higher system energy efficiency than vapour compression systems driven by electricity produced in conventional power plants. In 1993 an advanced 250 kW absorption heat pump for space heating and cooling entered the market; ammonia-water is the working pair. The system has been installed in a Dutch institutional building, and operates with a high seasonal PER (1.4) /IEA93/. Research is concentrating on the development of systems with high performance, high temperature lifts, high output temperatures, a wider range of application and lower cost. This includes the development of double-lift, double-effect and triple-effect units, generator/absorber heat exchanger systems (GAX) and new working fluids. A new working fluid for high temperatures (max. 260°C) is now available on the market. This fluid makes it possible to use cheaper construction materials as the corrosion rate is negligible /HPC94/.

11.4.6.2 Heat transformers (type II)

Heat transformers are used in some industries to upgrade waste heat to a useful temperature level. These systems use water and lithium bromide as the working pair. Current systems have a maximum delivery temperature and temperature lift of 145°C and 50°C, respectively. Heat transformers typically achieve PERs in the range 0.45 to 0.48. Only a few systems are in operation world-wide, the majority of them in Japan /HPC94/.

11.4.6.3 Hybrid heat pumps

The hybrid cycle is a combination of vapour compression and absorption. Here the evaporator is replaced by a desorber and the condenser by a resorber; an extra loop is added for the absorbent-refrigerant solution. The most common working pair is ammonia and water. In Germany three systems are in operation and another one in Hungary. COP ranges between 4 and 9 /IEA93/.

11.5 Developing country considerations

Heat pumps for heating only and heat recovery are scarcely applied in developing countries. The reason is that many developing countries are located around the equator, hence having a very limited space heating demand. Also, since capital is limited in these regions, the CFC-consuming equipment, to the degree it exists, is more likely to have a refrigeration function (food conservation). Therefore, it is assumed that the number of heat pumps and the annual CFC consumption for such purposes both are negligible. However, this situation may start changing towards the end of the 1990s. Centrally planned economies like the former Soviet Union, China, and most of the Eastern Europe today, all have average household energy consumption's far below that of the Western World. Economic reforms and emerging democracies will eventually yield higher living standards, which in turn will result in a higher domestic energy consumption. A significant problem in these regions is environmental pollution. Therefore, a higher energy consumption, including that for heating, should preferably not be based on direct combustion of oil or coal.

This could spur the demand for heat pump systems, resulting in a world growing market. All this is connected to a high degree of uncertainty and is highly dependent on political decision making and economic growth.

11.6 Forecast of refrigerant use

Since CFC production will halt from the end of 1994/95, future refrigerant supply for heating-only heat pumps will come from recycled/recovered CFCs from scrapped and retrofitted heat pumps, stocked CFCs by end-users, as well as HCFCs, HFCs and "natural refrigerants", particularly ammonia and hydrocarbons. Estimated CFC and HCFC demand for heating only heat pumps in 1993 was 1,000 and 800 tonnes, respectively. Total refrigerant demand is expected to grow 5% annually. When calculating the annual CFC demand for the period 1994 to 2005, it is assumed that 10% of the heat pumps are scrapped/retrofitted in 1994 and 20% after 1994. From 1994 CFC consumption is expected to cover leakage's only (no new installations). The above figures are relative to the total CFC pool (6,500 tonnes in 1993). Furthermore, it is assumed that HCFC demand declines 10% annually (scrapping only). HFCs are expected to cover 80% of the total need for alternatives, while ammonia and hydrocarbons will cover the rest.

A refrigerant demand estimate can be made at present and is given in Table 11.4.

Table 11.4 Estimated heat pump refrigerant demand [tonnes]. Ammonia demand is to be read as HFC equivalents.

Year	Type of Refrigerant				
	CFCs	HCFCs	HFCs	Ammonia	Total
1993	1,000	800	-	-	1,800
1994	585	720	470	115	1,890
1995	470	650	690	175	1,985
1996	375	585	895	225	2,080
1997	300	525	1,090	270	2,185
1998	240	470	1,270	315	2,295
1999	190	425	1,435	360	2,410
2000	155	380	1,595	400	2,530
2005	50	220	2,370	590	3,230

The reduced CFC and HCFC refrigerant pool (20% and 10% annually) will be reused/-recovered. Due to various reasons, only a fraction of the potential for recovery can be utilised as refrigerant, and therefore it is assumed that 60% of the available CFC and HCFC volume is actually recovered. Table 11.5 indicates the potential for CFC and HCFC recovery.

About 2,300 tonnes of CFCs will be made available for reuse between 1995 and 2000, which is about 20% more than the actual CFC demand for servicing existing heat pump installations.

Table 11.5 Estimated potential for CFC and HCFC recovery and reuse in heat pumps.

	CFCs		HCFCs	
	Potential for recovery	Available for reuse (60%)	Potential for recovery	Available for reuse (60%)
1994	650	390	440	265
1995	940	560	425	255
1996	850	510	400	240
1997	760	460	380	230
1998	680	410	360	215
1999	620	370	330	200
2000	560	340	310	185
2005	320	190	225	135

11.7 Concluding remarks

HCFCs are generally accepted as a part of the solution for a rapid CFC phaseout, and HCFC-22 is the most important refrigerant in this category. Many European countries are discussing regulations for HCFCs with a view to phasing them out more rapidly than has already been agreed under the Montreal Protocol. Germany, Sweden and Italy will ban the use of HCFCs in new equipment from the year 2000. Other countries considering bringing in earlier phaseout dates include Austria, Denmark, Norway and Switzerland. *HFC-134a* is currently applied for retrofitting of existing heat pumps which used CFC-12 and for charging of new installations. HFC-134a heat pump technology is considered fully mature for new systems. The demand for HFC-134a is expected to increase substantially in the next years. Moreover, *HFC and HFC blends* are expected to be available towards the end of the decade, thus resulting in a further increase in HFC consumption. *Ammonia* has recently attained a growing market share as refrigerant in large capacity heat pump systems in Europe. Halt in CFC production and further technology development, are expected to accelerate market penetration in Europe, as well as in Japan and the United States. Ammonia technology for small capacity heat pumps is expected to be available by the turn of the century. *Propane* is currently used in small capacity heat pumps in Europe. Technology development and improved safety measures will reduce safety hazards and improve public acceptability. Hence, propane, other hydrocarbons as well as hydrocarbon blends are expected to play an increasingly important role in the next years, especially in small and medium capacity heat pumps. *Carbon dioxide* is a promising long-term natural refrigerant, but is not expected to become of much commercial importance until the late 1990s.

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12 Refrigerant conservation

12.1 Introduction

To avoid any direct impact of refrigerants on the environment through their emission, refrigerant conservation is a major consideration in refrigerating system design, installation, and service. Conservation deals also with the needs for servicing existing equipment. As CFC and HCFC production is reduced to eventual termination, refrigerant supplies will dwindle and recovered quantities will be necessary for both developed and Article 5(1) countries. Limitation of emissions of refrigerant is a new issue, with a high potential of development. As it concerns all refrigeration and air-conditioning systems, it covers all applications of refrigerants. However, it is today rather difficult to quantify, because of the lack of reliable data.

12.1.1 Potential reduction of emission

Containment programs have only been implemented over the last 4-5 years, and results are only being reported now. This delay is mostly due to the fact that few countries have made recovery mandatory, and even fewer have developed global containment policies. Some initiatives come from the field, where refrigerants are starting to be considered as too expensive to be wasted. Among them, chillers end-users have been very active. Consequently, it is difficult to give valid statistics on containment today. However, the case of France /Sau94/ where results on reclaim have been gathered shows different steps. In 1992, without any regulation, 200 tonnes of recovered refrigerant (CFCs+HCFCs) were reclaimed. In 1993, after making recovery mandatory and carrying out a deposit-refund scheme, the quantity raised to 300 tonnes and the number of refrigeration companies concerned doubled from 200 to 400 out of 2500. In 1994, with the retrofitting of R-502 systems, the reclaimed quantity should rise to at least 500 tonnes, and the number of companies concerned already reaches about 1,000. This excludes recovery for reuse on site which is still much more difficult to quantify. This example tends to show that government incentives are necessary to reach development, and that making recovery a habit requires some time.

12.1.2 Definitions

Terms used in refrigerant conservation have not yet become standardised internationally, so the same terms may mean different things to different people. Furthermore, different meanings may be assigned in different countries. For the purposes of this section the definitions for recover, recycle, and reclaim have been taken from the latest draft of ISO/WI 11650R entitled "Performance of refrigerant recovery and/or recycling equipment" /ISO/.

. **recover:** to remove refrigerant in any condition from a system and store it in an external container.

. **recycle:** to reduce contaminants in used refrigerants by separating oil, removing non-condensables, and using devices such as filter-driers to reduce moisture, acidity, and particulate matter.

. **reclaim:** to process used refrigerant to new product specifications. Chemical analysis of the refrigerant shall be required to determine that appropriate specifications are met. The identification of contaminants and required chemical analysis shall be specified by reference to national or international standards for new product specifications.

. **dispose:** to destroy used refrigerant in an environmentally responsible manner.

. **containment:** the practice of designing, installing, servicing and disposing of systems so as to minimise leaks and other emissions from systems or storage containers and to avoid deliberate emissions.

. **mixed refrigerant:** used refrigerant containing levels of "other refrigerants" which exceed new product specifications for a single refrigerant or blend. This term is not to be confused with a refrigerant mixture which has been formulated by the chemical producer as a blend of several components and sold as a refrigerant.

12.2 Government options in encouraging refrigerant containment

Beside the application of the Montreal Protocol and its revisions that aim at phasing out production of Ozone Depleting Substances (ODS) over a few years, governments can help reduce emissions to the ozone layer by strongly encouraging containment. To be consistent with the environment at concern, CFCs recovery could have been made compulsory as soon as 1987. In addition to direct regulation, governments can encourage refrigerant containment in a number of ways including research and development, information dissemination, and financial incentives. A brief description of each approach and its advantages and disadvantages follows. They are valid, with due adaptation, for both developed and Article 5(1) countries.

12.2.1 Research and development

Research and development typically involves research on sources of emissions and technologies to address these. Governments may establish their own laboratories and/or fund industry research efforts. Projects for research and development may include high efficiency recycling and recovery equipment, low loss connectors, high efficiency purge units, and improved service practices. R&D is likely to be most effective when there are legal or financial incentives to implement the technologies and techniques developed.

R &D can reveal effective containment methods and technologies and is an unobtrusive method of encouraging containment. However, existence of an effective containment method or technology does not alone ensure that the method or technology will be used.

12.2.2 Information dissemination

Information dissemination can encourage containment by emphasising both why and how to contain. It may include providing materials and/or training on the role of CFCs and HCFCs in ozone depletion, the effects of ozone depletion, and technologies and techniques for reducing emissions during equipment operation, service, and disposal. Information dissemination may be targeted both at industry and the general public, and may be especially effective in changing the behaviour of more isolated segments of the industry, for whom ignorance of proper techniques has hampered containment. Information dissemination is likely to be most effective when legal or financial incentives to implement the technologies and techniques exist. Information dissemination may

increase general knowledge of both how and why to contain, improving containment where ignorance is the primary problem. However, knowledge of an effective containment method or technology does not alone ensure that the method or technology will be used. Moreover, populations that are isolated from the industry may also be difficult for government to reach.
For more details on information dissemination see also section 14.

12.2.3 Financial incentives

Financial incentives can encourage containment by making emissions more costly for users. Financial incentives may include sales taxes on refrigerants, deposit-refund schemes, and tax breaks for investing in recovery/recycling equipment or other refrigerant containment technologies. Unlike direct "command and control" regulation, financial incentives encourage containment without prescribing specific methods. Thus, they allow the market to find the most cost-effective containment measures and they encourage innovation.

Sales taxes or excise taxes encourage conservation of refrigerants by making it more expensive to replace them. A gradually rising excise tax on CFCs in the U.S. has been effective in increasing containment of CFC refrigerants. For instance, the tax has made it less expensive to recycle CFC-12 in motor vehicle air-conditioners than to buy new refrigerant, addressing a significant source of emissions.

Deposit-refund schemes involve collecting a deposit when a product is purchased and paying a refund when the used product is returned. The refund serves as an incentive to the user to collect and return used refrigerants. The deposit not only finances the refunds, but encourages more careful handling of the product by increasing the cost of new refrigerant. Two issues that must be faced in establishing a deposit-refund system are (1) how (or whether) refrigerants are traced back to the original manufacturer for collection of the refund and (2) how refunds for the bank of refrigerants in existing equipment, for which no deposit was collected, can be financed. Industry-sponsored deposit-refund schemes in Australia, Denmark and France resolved these issues by setting a centralised fund for deposits.

Tax breaks for investing in refrigerant containment equipment and technologies have been adopted by some states in the U.S. To the extent that they are tied to particular technologies, tax breaks leave the market less flexibility than either sales taxes or deposit-refund schemes.

Care should be taken to set taxes, tax breaks, and deposit-refund amounts at levels that will maximise conservation without being unduly burdensome. Ideally, a financial incentive will make anyone releasing any damaging material bear a cost equivalent to the cost borne by society (in terms of damage to human health and the environment). A number of scientific and ethical issues must be considered before attributing a monetary value to damage to human health and the environment resulting from refrigerant emissions. For instance, the U.S. EPA has developed a range of estimates that it has used as a broad guideline in developing its CFC and HCFC policies and regulations.

Financial incentives may be easier than direct regulations to develop and enforce, and more flexible than direct regulation as they allow the market to find the most cost-effective containment measures and maintain the incentive to innovate. However, it can be difficult to set financial incentives at a level that encourages containment without being unduly burdensome, and financial incentives cannot yet compel conservation. In case of market failures, such as inadequate information on recycling techniques and technologies, the effectiveness of financial incentives may even be hampered.

12.2.4 Direct Regulation

Direct regulation is the most traditional governmental approach to encouraging conservation and reducing pollution. For purposes of refrigerant containment, direct regulation may include establishing required service and disposal practices for air-conditioning and refrigerating equipment, containment standards and/or certification programs for air-conditioning and refrigerating equipment and recovery/recycling equipment /ARIDi/, and required training and/or operator certification programs. To the extent possible, standards should be performance based rather than technology based to encourage innovation. As is the case for financial incentives, care should be taken to set standards that maximise conservation without being unduly burdensome. Direct regulation establishes "floor" standards and practices across industry as required training and/or certification increases general knowledge of both how and why to contain. However, they are often less flexible than financial incentives, and more difficult to develop and enforce, given the large quantities and wide distribution of air-conditioning and refrigerating equipment.

12.3 Containment

Refrigerant emissions from cooling systems must be minimised to protect the environment. Fortunately, containment is consistent with the function and structure of air-conditioning and refrigeration systems. Cooling systems are designed as sealed units to provide long term operation. Containment is affected by both the design, the installation, and the servicing of the refrigerating system. Guidelines and standards are being updated with consideration to environmental matters and improved containment /ASHRAE, Nord 94/.

Containment is defined by an emission rate which can be measured and limited. Cooling system manufacturers have defined minimum tightness requirements to guarantee permanent operations during defined periods. ASTM E 479, one of the manufacturer's reference document, determines the maximum allowable leakage flow for a cooling system based on the period during which the system must operate without refrigerant recharge (5 years for a hermetically sealed system and 3 years for other systems), the refrigerant quantity that may be lost by leakage during this period without significantly affecting the operational efficiency of the system the refrigerant used, and the maximum operating pressures and temperatures in the system. Values of allowable leakage flows could be changed to take account of environment. For instance, In Sweden, the Environment Agency has measured an average leakage rate of 17% per year for stationary systems, and now requires a 5% rate /Nord94/.

12.3.1 Design

Every attempt should be made to design tight systems which will not leak during the service life as well as to minimise the service requirements that lead to opening the system. The potential for leakage is first affected by the design of the system. Manufacturers select the materials, the joining techniques, and the service apertures, and design the replacement parts. In addition, the manufacturer provides the recommended installation and service procedures. They are responsible for anticipating field conditions and for providing equipment designed for these conditions. Assuming that the equipment is installed and maintained according to the manufacturer's recommendations, the design and proper manufacturing of the refrigerating system determines the containment of the refrigerant over the intended life of the equipment.

Among recommendations for containment, leak tight valves should be installed to permit removal of replaceable components from the cooling system. The design must also provide for future recovery, for instance by locating valves both at the low point of the installation and at each vessel for efficient liquid refrigerant recovery .

12.3.2 Charge minimising

Minimising the refrigerant charge will also necessarily reduce the quantity of possible emissions. Because little attention has historically been given to the charge in installations, its quantity is not often known, except for small manufacturer-built equipment. Receivers are frequently vessels that enclose useless refrigerant stocks. Charging is often continued until the evaporator supply is considered satisfactory. Without the check of weighing the charge, installation could be overfilled with two harmful consequences: (1) a potential serious release of refrigerant, and (2) the impossibility of transferring the entire charge into the receiver. The receiver filling ratio should preferably be limited during nominal operation.

12.3.3 Installation

Proper installation of refrigerating systems contributes to the proper operation and containment during the useful life of the equipment. Tight joints and proper piping materials are required. Proper cleaning of joints and evacuation to remove air and non-condensables will minimise the service requirements later on. Proper charging and weighing techniques along with careful system performance and leak checks should be practised during the first few days of operation. The installer also has the opportunity to find manufacturer's defects before the system begins operation. The installation is critical for maximum containment over the life of the equipment.

12.3.4 Servicing

Refrigerant venting to the atmosphere should be minimised. All leaks should be located and repaired. Careful attention to proper cooling system operation will reduce the incidence of large leaks due to system malfunction. Special refrigerant handling and cleaning techniques are required to maximise containment. Use of disposable cylinders for refrigerants should be forbidden as their remaining heel is not recovered after use and contributes to the emission of refrigerant to the atmosphere.

12.4 Leak detection

Leak detection is a basic element, both in constructing and servicing cooling equipment, as it makes it possible to measure and improve containment of refrigerant. It takes place both at the end of construction by the manufacturer's, or at the end of assembly on the field, and regularly during the operation of equipment.

There are three general types of leak detection. **Global methods** indicate that a leak exists somewhere, but they do not locate the leaks. They are useful at the end of construction and every time the system is opened up for repair or retrofit. **Local methods** pinpoint the location of the leak and are the usual methods used during servicing. **Automated performances monitoring systems** indicate that a leak exists by alerting operators to changes in equipment performances.

12.4.1 Global methods

This method may be described as applicable any time the system has been emptied of its whole refrigerant charge. Two methods are used: one controls the cooling system, the other measures the presence of product in the air around it.

System checking:
- The system is pressurised using nitrogen or helium and isolate. A pressure drop within a specified time indicates leakage.
- The system is evacuated and the vacuum level is measured over a specified time to assure tightness. A pressure rise indicates leakage.

Refrigerant detectors:
Electronic leak detectors, installed in machinery rooms, may prove efficient provided that (1) they are sensitive enough to measure refrigerant that has been diluted in the air, and (2) that air is circulated properly in the room.

12.4.2 Local detection

The different local detection methods vary widely in their sensivity. Sensitivity levels to non-chlorinated refrigerants may be lower for certain methods. This sensitivity is usually given in p.p.m.(volume) but for the sake of clarity, they are often given in mass flow rates (g/year).

- Visual checks locate large leaks (100 g/year or more) by seeking tell-tale traces of oil at joints.
- Soapy water detection ("bubble testing") is simple, inexpensive and pinpoints leaks (50 g/year or more) when the operator is trained.
- "Tracer" colour added to the oil-refrigerant mixture shows the location of the leak. The tracer must be compatible with the various materials used in the refrigeration circuit.
- Electronic detectors using corona discharge, hot wire anemometer, or similar techniques can detect from 5 g/year to 100 g/year according to their sensitivity.
- Ultrasonic detectors register the noise of the leak. They avoid the use of a HCFC or HFC tracer when checking the tightness of a new installation yet provide the location of the leak.
- Electronic detectors based on infra-red spectroscopy are more sensitive than other electronic detectors (1 g/year).

12.4.3 Automated performances monitoring systems

Monitoring parameters such as temperatures and pressures meaningful to the coolant cycle, helps to monitor any change in the equipment. This monitoring provides information useful for carrying out diagnostics on the condition of the heat exchanger surfaces, proper refrigerant pumping, and shortage of refrigerant charge. Automated diagnostic programs are now being developed to produce pre-alarm messages as soon as a drift is observed. These developments are in their early stages, but their generalisation would give better control over refrigerant leaks. Equipment room monitors for HCFC-123 low pressure systems are currently used. On low pressure systems, it is also possible to control the tightness of the equipment by monitoring purge unit run time, which can indicate leaks.

12.5 Service practices, training

Service must be improved in order to reduce emissions. Such improvement, however, depends on the price end-users agree to pay, as emission reduction has so far proved more expensive than "topping off" cooling systems with refrigerant. It is necessary to make end-users understand that the price they use to pay for refrigerant must be spared and spent on improved maintenance. It is to be noted that such a step has already been taken in some cases, especially in countries like the U.S. where tax on refrigerants makes containment more cost-effective. Refrigerating systems must be tested regularly to ensure that they are well sealed, properly charged, and operating properly. During maintenance and scrapping of the system, refrigerant should no longer be released; instead, it should be isolated in the system or recovered. Special cautions are required to properly handle and clean used refrigerants. The equipment should be checked in order to detect leaks in time and thus to prevent loss of the entire charge. Special training is required to properly handle and contain refrigerants.

12.5.1 Service assessment

The operator must study the service records to determine if there is any history of leakage or malfunction. He/she should look for evidence that the equipment has been retrofitted to a different refrigerant or lubricant. The operator will also need to check the refrigerant saturation pressure at the measured temperature or analyse the refrigerant to assure it is the nameplated type. He/she will want to determine the best location from which to recover the refrigerant and assure he/she has the proper recovery equipment and recovery cylinders. The operator should also thoroughly check for leaks and measure performance parameters to determine the operating condition of the cooling system.

12.5.2 Maintenance documents

The existence of a maintenance document enables the user to monitor additions and removals of refrigerant with recovery. After a number of years, this information could be used for statistical comparison. Records of refrigerant quantities can indicate whether recharging operations are actually associated with searches for and repairs of leaks. Maintenance documents have been made mandatory by a number of countries, as it enables authorities to check the actual consumption of refrigerants.

12.5.3 Training

Installers, mechanics, and service operators require training. A number of countries have adopted a system of certification of technicians who handle refrigerants. This training would likely provide a basic understanding of the effects of refrigerants on the environment; recovery, recycling, and reclaiming refrigerants; leak checking and fixing leaks; and some introduction to new refrigerants. However, this one time and somewhat superficial training is by no means adequate on an ongoing basis. The service operator requires continual training to understand new high energy efficiency designs, new equipment with new refrigerants and lubricants, new low emission purge units, retrofitting requirements, and service practices. Such requirements call for a higher level of ability and training for service operators than has been required in the past. Many countries have recognised this and have launched recruitment efforts to attract capable new operators into refrigerating systems service. The service operators require continual training to understand and implement containment management of refrigerant. Some countries have recognised this need and launched qualification and certification programs that both upgrade the technical level of technicians and point out to the end-user that they are qualified to deal with refrigerants.

12.6 Refrigerant recovery

Refrigerant recovery equipment has been developed and is available with a wide range of features and prices. Testing standards have been developed to measure equipment performance for automotive /SAE/ and non-automotive /ISO/ applications. Refrigerant conservation requires defining the efficiency or completeness of the recovery. Many countries have adopted final recovery vacuum requirements of 0.3 or 0.6 bar, depending on the size of the cooling system and saturation pressure of the refrigerant. This provides for recovering 92 to 97 percent of the refrigerant. Some equipment may go further, but the final phase will take longer. Due to the ratio of the densities of liquid and saturated gas, recovery in liquid phase can be 30 to 40 times faster than in vapour phase. When all conditions have been combined for a quick transfer of the liquid, it is possible to achieve average flows of 50 to 500 kg/h which may be necessary to economically recover refrigerant from larger systems. The residual vapour remaining after liquid recovery will generally represent 20 percent by weight of the total refrigerant charge. Although liquid recovery is the quickest, vapour recovery methods may be used alone to remove the entire refrigerant charge as long as the time is not excessive which may limit the practical usage to systems containing up to 5 kg refrigerant (the most numerous ones). For larger systems and in order to reach the vacuum levels that are required in some countries, vapour recovery will be used after liquid recovery /Clo94/.

12.6.1 The recovery cylinder

Cylinders used for recovered refrigerants must comply with local and national requirements for pressure vessels, which can be very different in each country. Recovery cylinders may be delivered with an internal vacuum or with a holding charge and should be prepared according to the cylinder and equipment manufacturer's instructions.

Labelling - Recovery cylinders and the refrigerants contained in them must be clearly identified to prevent possible mixing of refrigerants and for the safety of the transporter. In addition, some countries require environmental warning labels.

Filling - Due to the uncertainties about the density of the recovered product because of the presence of oil and ambient temperature variations, recovery cylinders should only be filled with liquid up to 80 percent of their volume. A scale or other weight sensitive device, a liquid level switch, or a double valve have all been used for this purpose.

Retesting - Most countries require that cylinders be retested at regular intervals such as every five years or if some unusual tank condition is noticed.

Cleaning - To avoid mixtures, recovery cylinders should be dedicated to the same refrigerant or cleaned after each operation. Reclaimers routinely clean cylinders as part of their refrigerant processing.

12.6.2 Hoses and connections

Excessively small diameters or restrictions cause pressure drops that can easily double recovery times. Enlarging the hose diameter from 1/4 inch to 3/8 inch increases the flow by more than 40 %. Connecting to both high and low pressure circuits of the cooling system will reduce the recovery time. The refrigerant hose should be equipped with a valve to prevent refrigerant emissions and intake of air. Hose materials and construction should minimise refrigerant permeation and should be suitable for the refrigerant and lubricant type. Connections on existing systems are frequently lacking because recovery was never considered in design, except for large systems. Often, the only available connections are for the "manifold" fitted with pressure gauges. In order to carry out the liquid recovery, it may be necessary to create access in the circuit wherever this liquid accumulates. During maintenance, it is useful to make permanent, leak tight access to facilitate recovery because this operation will probably be repeated later. Since liquid recovery is very fast, the necessary time and expense to create a sufficiently large access may be justified for larger systems.

12.6.3 Liquid recovery

Recovery of the liquid is the quickest, and should be the priority when recovering quantities above 50 kg as time-loss is a decisive argument against carrying out recovery. Several techniques are available for recovering the liquid: by difference of static pressure, difference in temperature, centrifugal or pneumatic pump, or by compressor. The last technique is undoubtedly the most developed one right now.

Recovery by nitrogen overpressure consists of adding nitrogen pressure into the vapour volume of a system that contains liquid in order to push it into the recovery cylinder. This method is frequently used for low-vapour-pressure refrigerants such as CFC-11. It is simple and fast when there is access at the low point of the system but it cannot be recommended as it cannot recover the vapour and generates a 10% to 20% loss.

Use of a relative vacuum in recovery cylinders: the relative vacuum in an evacuated cylinder can create a transfer without any other equipment, and the refrigerant recovery will continue until equalisation of the pressures between the system and the cylinder. If there is direct access to the liquid in the system, it is possible to recover significant quantities of liquid without any other equipment by using 3/8-inch hoses. It can also help to extract residual vapour when recovering from tubing's and recovery equipment. However, it is limited to only small quantities.

Heat transfer: the simplest way of reducing pressure is to cool the recovery cylinder, for instance by storing it in a cold room beforehand. This method is limited by the nature of construction materials (- 20°C for standard cylinders). It is also possible to heat the refrigerant in the system to create a difference of pressure with the recovery cylinder. Some recovery units consisting of an electric heater and a pump are able to heat the water contained in the evaporator of chillers and pressurise the liquid refrigerant to make it flow into a recovery cylinder.

Gravity transfer: a transfer due to pressure difference can be prolonged using the difference of level between the system and the recovery cylinder. The flow rate will depend on the difference of level, the length and diameter of connection hoses, and the pressure losses in valves.

Recovery by centrifugal or pneumatic pump: these methods are frequently used for large volume as they are simple and efficient. Pneumatic pumps have, however, the ability to recover either the vapour or the liquid whereas prolonged operation of a centrifugal pump in vapour will deteriorate the pump. Liquid pumps must be equipped with safety valves as there is a risk of explosion if a valve is closed at the pump discharge, which is not the case with pneumatic pumps.

Recovery by pressurisation: recovery may be made either by the system compressor or by external equipment. Liquid can be recovered by units running with usual refrigerating compressors according to two different methods:

- Evaporate the liquid, compress it, and then recondense it before discharging it into the recovery cylinder. This is actually vapour recovery, and consequently slow.
- "Push" the liquid by using the compressor to maintain a pressure difference between the system and the recovery cylinder. Some recovery units have complex designs that may be suitable for systems in which there is only one access point to the refrigerant and only one valve on the recovery cylinder. The "push-pull method" may be used with any compression unit but requires two access points to the liquid in the system and two ports on the recovery cylinder.

12.6.4 Vapour recovery

This operation is necessary, since the only way of checking that all liquid has been evaporated is to lower the pressure in the system below the saturation vapour pressure of the refrigerant. Moreover, a number of countries require recovery into a vacuum. Extraction time of vapour is often considered to be too long, and may be due to residual liquid that remains in difficult-to-access low points. However, the only way of guaranteeing an efficient final emptying operation is by recovering the vapour. The most commonly used method of removing refrigerant vapour is the compressor/evaporator method. Besides using the relative vacuum of the cylinders or the heat transfer, which is not very efficient, technicians may use the following devices.

Recovery by adsorption: solid matrices have been developed that are capable of adsorbing various refrigerants. After recovery, this cartridge is returned to the workshop where refrigerant is extracted by heating and condensed in a cylinder. This method is not well developed.

Recovery by pneumatic pump with or without a condenser: pneumatic pumps can recover vapour refrigerant with volume flow rates in the same range as compression systems. Very low intake pressures of the order of 0.1 atm absolute pressure can also be obtained.

Recovery by vacuum pump: conventional primary vacuum pumps discharge into the open air; however, some special vacuum pumps can recover residual refrigerant, if equipped with a well-designed condenser. A new design of equipment - two stage vacuum pump plus compressor units - provides an economical solution for recovering the last fraction of refrigerant left in a system and may be done in idle time, for example, during the night, provided the recovery cylinder is large enough.

Recovery by compressor: this is the most used solution, and especially in the automotive air-conditioning application. Most compression recovery units are suitable for recovering vapour, even for low pressure values down to 0.1 atm abs (1.5 psia). Depending on the type of compressor they are equipped with - hermetic units, open units, dry piston or diaphragm compressors - recovery systems will have different costs and different maintenance requirements .

12.6.5 Performance of equipment

It is difficult for technicians to compare different equipment. In order to make the comparison easier, and also, in countries which certify equipment, to establish a consistent test method, standards for measuring recovery and recycling performances have been designed /Clo93/. ISO 11650, the international standard, or ARI 740-93 (U.S.) or NF E 35-421 (France) can be used, and are based on the same elements.
The measured performances are:

- Vapour refrigerant recovery rate (kg/h)
- Liquid refrigerant recovery rate (kg/h)
- Final recovery vacuum (bar)
- Recycle rate (kg/h)
- Purge loss due to air purge, clearing unit, and oil removal are limited generally to less than 3% by weight.
- Trapped refrigerant in % by weight and in kg. Indicates the potential for mixing in recovery or recycling units rated for multiple refrigerants.

12.7 Recycling and reclamation

12.7.1 Recycling

Recycling is one available option for dealing with recovered refrigerants. There are other options like destruction of the refrigerant. Unlike reclaiming, recycling does not involve analysis of each batch of used refrigerant and therefore does not quantify contaminants nor identify mixed refrigerants /Kau92/.

Unlike direct reuse, recycling equipment is expected to remove oil, acid, particulate, chloride, moisture, and non-condensable (air) contaminants from used refrigerants. These recycling performances can be measured according to standardised test methods (see 12.6.5). In these tests, for each refrigerant a standard contaminated refrigerant sample is prepared which is representative of severe service such as a hermetic compressor burnout. The recycling equipment is operated according to the instructional manual to process refrigerant until the filter-driers require changing. At the time of the filter-drier changeout, the recycled refrigerant is analysed for each contaminant. Performance results show at which level the contaminated sample has been cleaned up. If recycling is performed as well as recovery, the recovery parameters described in 12.5 are also applicable, including the potential mixing rate of refrigerant when operating (see 12.6.2).

Altought some current recycling units are capable of processing the contaminated refrigerant sample to levels close or equal to new /ARI700/ or reclaimed refrigerant, some restrictions have been placed on the use of recycled refrigerant because it is not usually analysed before each use. This has even led to legal restrictions on recycled refrigerant, as in France where it cannot be used in system other than the one it came from. In the U.S., a broad based industry group has put together a document /ARI94/ which defines recommended procedures as well as contaminant levels for recycled refrigerants used in cooling systems for the same owner.

A variety of recycling equipment is available over a wide price range. Right now, the automotive air-conditioning industry is the only application which prefers the practice of recycling. Acceptance in other sectors depends on national regulation, recommendation of the cooling system manufacturers, existence of another solution such as a reclaim station, variety and type of systems and the preference of the service contractor. Recycling with limited analysis capability may be the preference of certain developing countries where access to qualified laboratories is limited and shipping costs are prohibitive. In most cases, there are no inexpensive field instruments to measure the contaminant levels after processing. Drawing a laboratory sample and obtaining an analysis may cost $40 US for a single contaminant and $125 for a complete analysis.

12.7.2 Mixed refrigerants

Mixed refrigerants are a concern because of the:
- Impact on performance and operation;
- Effect on materials compatibility, lubrication, equipment life, and warranty costs.
- Increased service and repair requirements and higher operating costs.
- Reintroduction of used refrigerants into the commerce stream.
- Inability or high cost of separating refrigerants.
- High cost of disposal and loss of refrigerant for future service.

This condition of mixture can be caused by chemical reactions such as in a hermetic compressor motor burnout. It is more likely caused by service practices such as failing to recognise which refrigerant is contained in a system, recovering refrigerant in a cylinder that already contains another refrigerant, or consolidating refrigerant in larger batches. Mixtures can also happen when using one recovery or recycling equipment for different refrigerants without vacuuming it /Manz91/.

The following steps can be taken to prevent or minimise the probability of mixing refrigerants:
- Properly clear recovery units or dedicate recovery units to a specific refrigerant.
- Dedicate cylinders to a specific refrigerant.
- Test suspect refrigerant before consolidating into larger batches and before attempting to recycle or reuse.
- Assure that cylinders are clean.
- Keep appropriate records of refrigerant inventory.
- Cylinders used for recovered and/or recycled refrigerants should be suitably marked.

It is very difficult to determine the presence of mixed refrigerants without a laboratory test. If the nature of the refrigerant is in doubt, the saturation pressure and temperature may be checked and compared with published values. A thorough review of the service history, if existing, and an understanding of the current problem may provide additional insight. Field instruments capable of identifying refrigerants at purity levels of 97 % or better are still under development.

Recycling equipment can neither detect nor separate mixed refrigerants. Except for automotive air-conditioning, there is consequently much discussion going on about where and under which conditions recycled refrigerant may be used.

In automotive applications where only CFC-12 and HFC-134a are being used, standards have required separate recycling equipment. In addition they have adopted unique vehicle service ports and service equipment fittings to prevent inadvertent mixing. Hoses will have separate connectors for CFC-12 and HFC-134a cooling systems and must be properly labelled /SAE/. Instruments capable of identifying CFC-12 and HFC-134a at levels of purity between 90 and 96% are being introduced to the market.

12.7.3 Reclamation

Reclaimed refrigerant refers to refrigerant which has been processed and verified by analysis to meet new product specifications such as given in ARI 700-93 /ARI700/.

Reclaimed refrigerant can be used in any system without threatening it, as contamination can lead to system failure. This has the advantage of avoiding possible system breakdowns which would lead to further refrigerant emission. As reclaimed refrigerant meets new product specifications, it often has the support of equipment manufacturers. Under the warranty period, these new product specifications support the warranty given by the manufacturer. Reclaimers will typically have the ability to analyse incoming refrigerant, to process the refrigerant as required, and to clean and fill the recovery cylinders. Analysis of out coming refrigerant will make it possible to assess the refrigerant specifications. Reclaimers will also typically provide shipping and labelling instructions and furnish or recommend cylinders. Reclaiming has the advantage to make it easily possible to measure amounts of refrigerant which have actually been recovered. It requires a costly infrastructure, and so may only prove profitable when the potential for return of recovered refrigerant is large enough.

12.8 Refrigerant disposal

12.8.1 General

Two installation types are available to destroy CFCs.
- Public or commercial installations have the advantage of being accessible in return for payment. They are often "generalist" and, therefore, capable of treating several families of chemical products.
- Other installations have been designed for the internal needs of CFC manufacturers. These installations are not necessarily available to treat products other than those used by the manufacturer.

12.8.2 Destruction methods

The general method of destruction is based on incineration of refrigerants and on scrubbing combustion products that contain particularly aggressive acids, especially hydrofluoric acid, HF. The number of usable incinerators is limited mainly by their resistance to hydrofluoric acid. We know that CFCs, and more particularly halons, burn very poorly since they are even used in fire fighting. In order to be incinerated, they must be mixed with fuels in specific proportions /DES92/. Appropriate destruction requires that materials making up the installation are resistant to the products to be destroyed and to the effluents, destruction is complete, that residual products can be eliminated, and that a **destruction efficiency (D.E) threshold** is defined. The threshold considered as being realistic is 99.99% on a mass basis. In other words, a maximum of 1 ten thousandth of the initial product is rejected into the atmosphere. Note that most countries in which there are incinerator installations have regulations and standards that define requirements about the limitation of liquid or gaseous emissions.

Five existing technologies appear to be suitable: incineration with liquid injection, cracking, smoke oxidation, incineration in rotary furnaces, and incineration in cement kilns. Two of these technologies are widely used and have been specially tested for the destruction of CFCs and have the required D.E. of 99.99%. These are liquid injection and rotary furnace incinerators. However, installations equipped with these types of incinerator do not necessarily resist combustion products; therefor they must also be equipped with scrubbers to eliminate acids. The cracking technique also reaches the destruction efficiency threshold. Cracking reaction vessels were specially designed for destruction of CFCs. This type of reaction vessel has been used since 1983. Units built on the cracking principle are capable of treating 800 to 1600 tons/year.

In addition to these destruction techniques, it is also possible to destroy CFCs in industrial processes. This is the case for the aluminium degassing process in second melting. In order to eliminate hydrogen inclusions that make metal brittle, CFC-12 is a replacement product for hexachlorethane and has the advantage of low toxicity. In this process, CFC molecules are destroyed at a very high temperature in the molten aluminium bath

12.8.3 Needs for destruction

Destruction plants exist in Europe, Japan and North-America. Running costs announced by Japan for a plasma destruction system is about 5 US $ / kg /Hot94/. However, it is probable that total destruction will be fairly low in the refrigeration industry, since the demand for CFCs will remain high. Even most mixtures will be separated through distillation which permits reuse of the component refrigerants.

12.9 Developing countries aspects

The ten year grace period for use of CFCs in Article 5(1) countries under the Montreal Protocol serves to diminish the sense of urgency in practising refrigerant conservation. However, the lower production quantities of CFC refrigerants after the developed country phaseout in 1996 will serve to increase the urgency. The hierarchy of needs in Article 5(1) countries is somewhat different than in developed countries, and is as follows:

1. To maintain systems in proper operating condition including tightening up systems by finding and repairing leaks. The relatively low cost of labour in Article 5(1) countries compared to buying parts or equipment makes this option attractive. The knowledge required is available from professional associations.
2. To recover refrigerant for reuse before servicing systems. The barriers are the lack of training on recovery, the need to maintain equipment, and the lack of cylinders. The reuse also requires either recycling equipment, with the barriers of cost and servicing, and/or reclaiming centres to clean the refrigerant to new product specifications. Some countries may choose to emphasise recycling equipment with screening test equipment to target severely contaminated refrigerant for destruction. Other countries may choose to set up reclaiming centres. UNEP distributes lists of equipment from manufacturers around the world.
3. To select HCFCs or non-ozone depleting refrigerants and technologies for new system installations. The growth in Article 5(1) countries will give a larger weight to new systems relative to existing systems compared to developed countries. In general, the cost of such systems is expected to be comparable to installing CFC equipment, which is still permitted for developing countries. However, the cost of CFC equipment is expected to rise as world-wide CFCs production falls off rapidly.

4. To retrofit or replace existing systems to use HCFCs or non-depleting refrigerants. Labour intensive retrofits may be attractive in some instances due to the relatively low labour rates.

There is no shortage of leak detection devices, recovery/recycling equipment or alternative refrigeration systems available from developed countries. Technology for refrigeration systems produced in developing countries may be outdated so that Article 5(1) countries may be required to spend larger sums to purchase equipment and systems from developed countries. Therefore, consideration in distributing Multilateral Funds to Article 5(1) countries should be given to updating manufacturing technology in those countries which currently produce refrigeration systems, and to help offset the costs required to accomplish the first three goals above.

Public awareness and education programs will help to bring about better refrigeration conservation programs. In addition, government actions to prohibit the venting of refrigerants during service will greatly enhance this effort.

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13 Developing country aspects

13.1 Introduction

13.1.1 Current situation

Since the last review, the development within the field of refrigeration technology has proved to be different from the development expected. This means that the technological aspects of a developing country now can and will be assessed from another point of view than first assumed. The most important aspect in this development is to determine the kind of refrigerants to be used in the individual developing country.

Apparently, this choice may seem easy, but in many cases it is found that the choice depends on whether the individual developing country has a refrigerant production, whether there is a production of refrigerating compressors etc., or whether only refrigerating plants are produced - including domestic refrigerators for the home market or for export. The developing country has to comply with the development going on in the rest of the world if export production is the question. The fact is that products containing refrigerants deviating from the receiving country's opinion of the demands on refrigerants will not be accepted in that country. This matter will naturally affect the technological design of the future refrigerating plants, also the plants in the individual developing country. Furthermore, the situation is difficult because in certain European countries, there will in future be used flammable refrigerants, particularly hydrocarbons. Such a choice of refrigerant will have far-reaching consequences in the individual developing country.

However, it is also known that many products are produced under licence and that means rapid technology transfer.

The largest problem is the smaller repair shops. At present, these small businesses are not able to handle inflammable refrigerants, neither compared to know-how, equipment nor the lay-out of the production facilities. Maybe they will get the same problems with the HFC types.

One cannot recognise the consequences. Therefore, combined with the introduction of a new technology, the absolutely most important matter in future will be training of the staff maintaining refrigerating plants which are not under guarantee any more. Moreover, intensified training will imply that the companies and service staff get used to a dynamic development within the field of refrigeration technology.

As regards technology, it shall be stressed that no temporary or short-term solutions are introduced. Developing country technology will be identical with the technology used in the developed countries. If temporary or short-term solutions are made, it must be expected that upgrading will be anticipated within a relatively short period.

13.1.2 Categories of developing countries

There are fundamentally two distinct categories, namely:

i) Large countries with relatively sophisticated CFC related technologies coupled with populations numbered in hundreds of millions.

These countries have a relatively developed industrial base. In China virtually all refrigeration and air conditioning equipment was produced nationally, albeit generally of outdated design, and the country is well provided with test and research institutes carrying out refrigeration work. The situation in India is believed similar.

China, India and Brazil all produce CFCs with India thought to have recently invested in expansion of this production. The price of CFCs in India is still low and there is no incentive to recycle them. China and India have plans to introduce HFC production (funded by the Montreal Protocol) and convert CFC to HCFC production. All current CFC producers can convert to HCFC production (CFC-12 to HCFC-22) provided the relevant feedstocks are available.

Countries like China, India and Brazil have strong industry associations. Knowledge of CFC phaseout technologies is relatively good.

ii) Other developing countries with smaller populations are characterised by:

- reliance on imported CFCs
- local equipment manufacture limited to assembly
- weak industry associations
- lack of up-to-date information on available CFC phaseout technology.

13.1.3 Factors most developing countries have in common

Loose government control. Even in the Chinese case where an outsider would assume tight control over all activities was maintained by central government, the liberalising of the economy and relinquishing of state economic control over individual industries has left a situation where methods of enforcing e.g. CFC recovery legislation cannot be defined.

Low per capita income. This has negative and positive aspects from the CFC phaseout point of view. The negative aspect is that developing country inhabitants with limited purchasing power will be exposed to higher world prices and suffer disproportionately from CFC phaseout. The positive aspect is that CFCs are expensive by comparison with a mechanic's time making refrigerant recycling innately cost effective. (See paragraph. 4.2).

Low service standards. This is not universally true. There is frequently a sharp difference between service centres maintained by manufacturers for the purposes of servicing equipment under their guarantee, and the facilities available for equipment service when the guarantee period has expired.

Many developing countries manufacture or assemble equipment for export to e.g. European markets with stringent regulations that currently prevent the import of any CFC containing appliances. This relates principally to domestic refrigerator production. CFC phaseout in such countries can thus often be driven by regulations in their export markets.

13.2 Technology transfer

13.2.1 General

Much has been written about the need to ensure that undertakings made by developed countries to make CFC phaseout technology available to developing countries are kept. Such pronouncements that presumably refer to general political comments miss the point. The technologies concerned are usually the property of private enterprises and therefore are not within control of politicians making these statements.

13.2.2 Types of technology transfer

i) Manufacturers (frequently of domestic refrigerators) can have an existing close relationship with an established developing country manufacturer. Frequently (though not always) non-CFC technology transfer is made available to the developing country company at a certain fee (which varies from low to substantial) as an upgrade to an existing license agreement. The developing country production may form part of the technology supplier's global production strategy in which case non-CFC conversion is in his interests.

ii) Independent producers of refrigeration equipment in the larger developing countries (e.g. China) can manufacture equipment at lower prices than in the high wage developed country economies. Thus technology transfer negotiations are inhibited by the fear on the part of potential technology suppliers that they may face competition in world markets from the very companies to whom they have sold technology. The difficulty of imposing market restrictions on licensed products reinforces this.

Indigenous development of non-CFC solutions is not considered acceptable by the funding institutions. It is argued that the risks inherent in implementing "home-grown" technology is too great. Where a suitable technology partner simply cannot be found, the Montreal Protocol could consider funding local developments.

13.2.3 The role of HCFC based technology

The current use horizon for HCFCs in developing countries is liable to be greater than for developed countries. This may change in the not too distant future, but it may be arguable that developing countries should take advantage of this aspect.

The reasons for this are:

i) HCFC refrigeration technology is becoming redundant in developed countries by virtue of strong local pressures to eliminate ODS use where at all possible. Thus the export of HCFC refrigeration technology (e.g. for low temperature commercial refrigeration) represents a commercial opportunity rather than a threat to developed country technology suppliers.

ii) Current CFC producers can convert some CFC plants to HCFC production if they were designed for the higher pressures used to produce HCFC-22. A current Chinese project submitted for funding is based on conversion of an existing CFC-12 plant to HCFC-22 production.

    Existing hydrogen-fluoride used for CFC production is used with chloroform to produce HCFCs. Chloroform is readily available world-wide.

iii) Non-availability of CFC-12 and R-502 (where used) suggests dependence on HCFC-based drop-in replacements for existing equipment. Agreements could be made with developed country producers for import of remaining blend components and mixing of blend locally.

On the other hand, a negative aspect of this approach is that additional investment made in production processes may be wasted if HCFCs become the subject of accelerated phaseout schedules under the terms of the Montreal Protocol. Also increasing controls on HCFC use in export markets (e.g. the EC) may provide a constraint.

13.2.4 Type of Montreal Protocol assistance

i) Investment projects for HCFC (HFC) based refrigeration equipment. There will comprise equipment costs, engineering development, training and some incremental production costs, along with technology transfer fees (in some but not all cases).

ii) Technical Assistance projects. Where existing equipment manufacturers want to convert their own designs to non-CFC use (e.g. commercial equipment manufacturers) established manufacturers of similar equipment in developed countries provide advice on how to develop the developing country designs. This is a different category to technology transfer and far less threatening from the point of view of a developed country equipment manufacturer.

13.3 Special technology for developing countries

13.3.1 Energy

Many developing countries are short of electrical generating capacity. Refrigeration equipment may account for a higher percentage of domestic power consumption than in developed countries. Any increase in energy consumption of either domestic, commercial or industrial equipment is undesirable.

Thus all CFC phaseout solutions, whether retrofitting existing systems or the production of new equipment, should provide systems of at least comparable levels of energy efficiency to those of CFC-based systems. No specific energy saving projects are admissible under the Montreal Protocol Fund as this lies outside its terms of reference. However, techniques of planned maintenance that will improve energy consumption of commercial and industrial plant can be included in training courses at no extra cost. Technical assistance projects can likewise include techniques of equipment design to improve energy efficiency.
Current developed country technology solutions in both areas fulfil this criteria and import of same will thus satisfy this requirement.

At least one developing country (China) has addressed the energy problem simultaneously with CFC phaseout and sponsored the development of energy saving refrigerant blends. In the Chinese case these are based around the use of HFC-152a and hydrocarbons in domestic refrigerators. The government believes that a 5% reduction in energy consumption of these appliances can be achieved with significant consequences for the country's hard pressed power generation sector. Further development needs to be seen.

13.3.2 Premature retirement of equipment

The premature retirement of domestic refrigerators is particularly severe in countries where low income and need for domestic refrigeration (occasioned by climactic conditions and/or food scarcity) make these appliances an expensive necessity. Suggestions valid in more prosperous developing countries such as discounts off purchase of new refrigerators are not valid in countries where a refrigerator may be made to last 20 or more years by virtue of several repairs. Here the absence of a *proven* retrofit alternative for domestic refrigerators is a problem. Any calculation to estimate the costs of compensating owners in full for the loss of refrigerators quickly shows the impracticality of this approach. However, three component blends of HCFC-22 / HCFC-124 and HCFC-152a are proven retrofits for small CFC-12 equipment with more than one million retrofits already done.

13.4 Refrigerant recycling and reclaim (R/R)

13.4.1 Categories in developing countries

i) Domestic

ii) Commercial refrigeration equipment. This comprises coldstores and transport refrigeration equipment in addition to refrigeration equipment found in retail premises.

iii) Mobile Air Conditioning (MACs). Since many developing countries are situated in tropical climates, MACs is frequently an important sector and significant user of CFC-12.

iv) Chillers

The potential for recovery depends on the particular mix of domestic and commercial equipment existing in the country concerned. Little refrigerant is generally recovered from domestic systems where charges are small (typically 150 grams). When refrigerators suffering from leaks are brought for repair they usually have lost their -small- charge. CFC-12 domestic refrigerators constitute a potential user of regenerated CFC-12. Only when brought for another type of repair involving breaking the refrigerant circuit (e.g. replacing the compressor) will the small charge be available for recovery, since domestic systems are not equipped with any means of storing refrigerant while repairs are carried out. Commercial equipment in some developing countries differs from that in developed countries in that there exists a large number of small display cases constructed in virtually the same way as domestic systems; they employ capillary tubes as the expansion device and therefore are not equipped with receivers to store refrigerant while repairs are made. Often the same small manufacturers make domestic refrigerators and display cases in almost the same way using labour intensive hand crafting methods. Though employing system charge 4-5 times those of domestic systems, little of this will be available once a leak has occurred. As with domestic systems though the absence of a receiver means that the charge is recoverable whenever a repair is made which involves breaking the refrigeration circuit. Commercial systems with larger charges do not generally provide a significant source of recoverable refrigerant. This is because refrigerant can be stored in the receiver except when high side repairs such as compressor replacement are being carried out. However where preventative maintenance is practised routine tests may indicate crankcase oil contamination in which case the refrigerant would be replaced. Retrofit schemes make the entire charges of systems available for recovery. Motor burn-outs from semi-hermetic and hermetic systems yield highly contaminated refrigerant.

Methods of recycling refrigerant are either by a central reclaim plant which produces refrigerant to the standard of virgin refrigerant (ARI 700-93 or similar) or mobile recycling machines which cannot handle severe contamination resulting from a motor burnout. These are adequate for most other contamination although their output can never be guaranteed. Capillary tube systems and domestic systems in particular require the highest quality refrigerant and therefore the use of refrigerant treated by a simple recycling machine is not advisable.

The foregoing shows that the amount of refrigerant available for recovery and the way this should be treated is a complicated function of the type of equipment prevalent in a particular country and whether retrofit is being practised. In some developing countries erratic power supply voltages mean that commercial compressors have an average lifetime as low as 2 years meaning that significant amounts *will* be recoverable from burnt-out systems but this will be heavily contaminated and require treatment by a central reclaim plant. Another factor which complicates the organisation of a reclaim scheme is the way refrigerant is distributed and whether or not it is produced in the country. A CFC producer can always use contaminated CFC as a feedstock for producing new CFC and this is certainly the best way of organising a central reclaim scheme. Among other things, a homogeneous distribution network will be in place that can be used to collect refrigerant as well as distribute it and the final product will be tested as a matter of course. This only works of course for as long as the producer makes CFCs. The length of time production continues can be affected by both individual country strategies *and* parent company policy where the producer is part of a multinational group.

MACs recycling schemes tend to operate in a closed loop of refrigerant recycling and re-use. Significant quantities are recoverable since leaking systems usually still have some of the approximately one kg CFC-12 charge in the system when brought for repair, but these systems are not equipped with conventional receivers and thus refrigerant must be removed from the system whenever repairs on the circuit are carried out. Being open drive systems, severe contamination from burn-outs never occur. For the same reason, these systems are particularly tolerant of refrigerant contamination. Thus a simple recycling machine is admirably suited for treating refrigerant recovered from MACs systems (indeed they were originally developed for this sector). Refrigerant will not generally leave this closed loop unless retrofitting to HFC-134a is being carried out when it is conceivable that surplus would be presented to a central reclaim scheme.

13.4.2 Developing country approach

In countries where basic survival is a daily task for many, the notion that effort and expense should be expended on an unseen environmental hazard is difficult to accept. However, the level of concern in such countries (e.g. the Philippines) is often surprising. The weak industrial structure and industry associations combine to make practical organisation of R/R schemes difficult. In particular finding a group which has the interest and expertise to take on management of a scheme but is not a partisan element among refrigerant importers, is difficult. This is particularly true where refrigerant is imported into the country concerned. Often a number of companies subsequently distribute the refrigerant. These frequently are the sole agents for a particular overseas producer and an atmosphere of intense competition can exist between them.

The relatively high value, however, of CFC refrigerant by comparison with a refrigeration technician's time, means that recycling is intrinsically more cost effective than in developed countries and is frequently practised informally. Indeed recovery equipment is often locally made by service technicians. The resultant product is of course of uncertain quality. The attached graph demonstrates this by presenting the ratio of local CFC cost to an hour of a mechanic's time for a number of European countries and the Philippines, a typical smaller developing country.

Schemes like this can be considered. Local equipment manufacture should be investigated, especially for simple recovery machines. If there is a prevalence of certain types of commercial equipment, these can be tailored to suit.

The organisation of the scheme *must* be based on profitable activity for all concerned. To this end a feasibility study should be carried out to determine the right mix of recycling equipment, recovery equipment and central reclaim facilities that would be required. Clear, financial incentives must exist at every stage of the operation such as cash payments for contaminated refrigerant and an new CFC/reclaimed CFC price differential. The feasibility study should demonstrate the profitability of the central reclaim scheme. The scheme should include steps to assure the reclaimed CFCs quality, e.g. participation of local institute/university in batch testing the product. Training of service technicians is important (see section 13.5) and a legislative framework is required (see section 13.6).

The disposal of incompetently recovered non-recyclable refrigerant mixtures will be a problem in countries with no high temperature (1100 C) incineration facilities, which is generally the case.

13.4.3 Type of Montreal Protocol projects

Feasibility Study as described above.

An Investment Project where costs of equipment can include provision of or subsidy of recovery equipment for service technicians.

13.5 The service sector

13.5.1 Containment

Training will enable service technicians to acquire skill updates that will assist them to reduce emissions during service work and modify installation methods to produce systems which leak less (using brazed joints instead of mechanical) and where service operations can be performed without refrigerant loss (suitable valves should be provided to facilitate this; also where appropriate valves are installed to isolate refrigerant that can subsequently be recovered in liquid form). An assessment should be conducted on service practices in individual developing countries to determine exactly what needs to be taught to achieve good practice in repair and installation.

13.5.2 Recycling

Technicians will need both skills and motivation to assure their active participation in R/R schemes.

13.5.3 Training

A comprehensive training course is required that addresses areas such as the background to CFC phaseout and why it is necessary. The motivation to participate in R/R schemes and take extra time over service operations will only make sense to a service technician if he is aware of the importance of such activities in the preservation of the environment. The improvement of service techniques and use of recovery/recycling equipment and techniques of retrofitting existing equipment with HCFC and HFC based replacements must also be addressed.

13.5.4 Type of Montreal Protocol project

The Training Project would involve the training of local refrigeration teachers by trainers from developed country Training Colleges specialising in elements described in 13.5.3 above; the purchase of equipment required (recovery and recycling machines, refrigeration equipment on which to practice) and the payment of teachers' salaries together with possible compensation for time lost by technicians during training.

Such a course would typically last three days if carried out full time and is aimed at training all the countries' technicians within a given time period. Existing refrigeration courses are updated to include this material. Participation may be made a legal requirement (see below). Its actual form is a function of numbers to be trained and facilities available and should be tailored accordingly.

13.6 Institutional strengthening/legal

13.6.1 Legal

Legislation is generally required. In addition to ratification of the Montreal Protocol itself, a CFC tax/levy may be required. Various permutations of the concept of making CFCs more expensive in order to encourage recycling are in operation world-wide. In developing countries this idea is frequently resisted by government on the grounds that it unfairly penalises an already hard pressed sector of the population. It may be necessary to make CFC emissions illegal. This is of limited practical significance since emitting CFCs is an invisible crime. However, it appears to be a necessary underpinning in most countries to other legislation such as showing evidence of appropriate participation in R/R schemes such as receipts from reclaim centre etc. This is often hard to enforce in developing countries where the relevant inspectors, if they exist, are under-resourced. Consideration should also be given to mandatory participation in a prescribed training course for anyone engaged in refrigeration or air conditioning service work.

13.6.2 Institutional strengthening

The establishment of a local CFC phaseout bureau can address the problems common in developing countries. For instance, shortage of current information can be overcome by collection and dissemination of up-to-date technical information regarding CFC phaseout. Where difficulties of disbursing funds to projects arise, the bureau can work with the appointed bank to disburse Montreal Protocol funding at appropriate stages in projects and thereby minimise wastage or fraudulent diversion of funds. Country Program work can be managed and recommendations prepared for presentation to government for legislation following canvassing of relevant industry/user bodies.

13.6.3 Montreal Protocol Project types

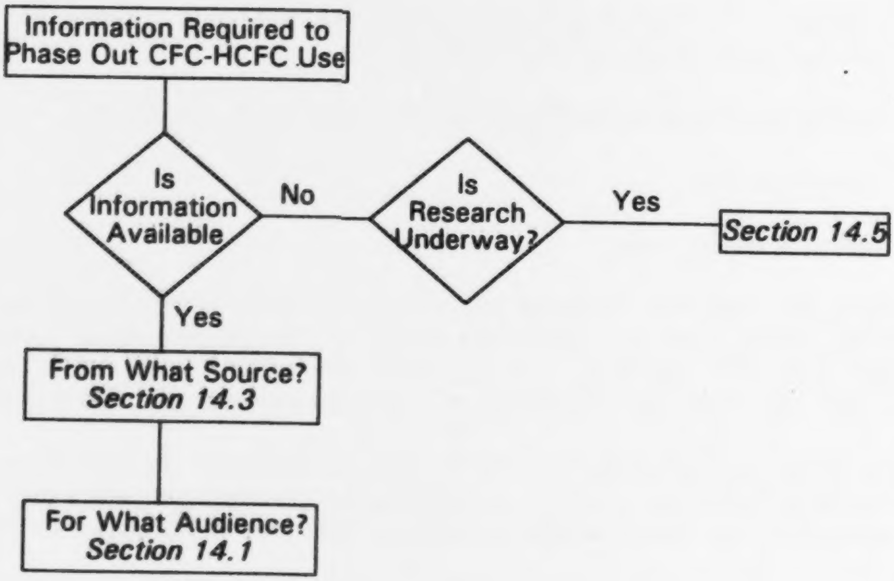
Several types of projects are being considered. For further information, publications by UNEP/IE DAC and the Executive Committee of the Multilateral fund should be consulted.

14 Research co-ordination and information dissemination

14.1 Introduction

The purpose of this section is to enumerate the types of information that must be in the hands of "decision makers" if the phaseout of CFCs and HCFCs are to proceed in an orderly fashion. This includes information on the science of atmospheric ozone depletion and global warming. Phaseout data must include the most current information on alternative refrigerants and alternative cooling technologies. Scientific, technological, regulatory and economic information is changing rapidly and those who make policy or investment decisions need to ensure that they are using the latest, most accurate information. Wherever possible, the reader is referred to organisations, periodicals, studies, or other sources of needed information. The lists included in this section are representative; they should not be considered all-inclusive.

Figure 14.1 The content and structure of this section


Information Required to Phase Out CFC-HCFC Use
Is Information Available
No
Is Research Underway?
Yes
Section 14.5
Yes
From What Source? Section 14.3
For What Audience? Section 14.1

The term "decision makers" refers to anyone along the chain of people making policy or equipment decisions. This includes government environmental officials, equipment and refrigerant manufacturers, installation and maintenance personnel, building owners and managers, consulting engineers, and facility operators. It is important that information be in a form that is appropriate for each audience.

It is important that decision makers have access to reliable, unbiased world-wide data. This should include success stories as well as learning from the experiences of programs that have been unsuccessful. Conservation, recovery, recycling and retrofitting are activities whose success will depend on the sharing of information.

Also listed in this section is pertinent research underway that is aimed at providing information which is key to CFC/HCFC phaseout. This section also attempts to identify the key areas in which co-operative research and developmental efforts are needed to generate additional information for these decision makers in government and industry.

The content and structure of this section is illustrated in Figure 14.1.

14.2 Information required to phaseout CFC and HCFC use

This section addresses, in general terms, the types of information needed by decision makers to phaseout ozone depleting substances (ODS). Section 14.4 addresses who the audiences are for this information and how it will be used.

Requirements for information cover a wide range of topics:

- basic scientific information on stratospheric ozone depletion, global warming, and the role of ozone depleting substances (ODS)
- data on basic refrigerant properties, as described in Section 2: system engineering, and equipment design and manufacturing
- retrofitting of existing equipment, service requirements, and training
- regulations, and
- financing mechanisms.

Both short- and long-term measures are being developed relative to CFC and HCFC alternatives. While there are immediate needs for information about the problems associated with the near-term ban on CFC production (conservation, recycling, "transitional" replacements), information on long-range alternatives is also important.

Attention should be paid to the information needs of developed countries as well as the special needs of developing countries, recognising that developing countries may not have ready access to some of the information needed to make prudent refrigerant decisions.

The sheer volume of specific information that is required or available to make refrigerant or equipment decisions precludes any attempt to list even the most important needs in a report such as this. Rather, the following sections describe topical areas where information is important to the developing of alternatives.

14.2.1 Environmental science

Countries must have access to the latest scientific findings with respect to the stratospheric ozone layer, global warming, and the role of ozone depleting substances. The information should allow those involved with refrigeration and air conditioning (manufacturers, installers, government officials, etc.) to understand these environmental concerns, enable them to inform the public and persuade them to act in a responsible manner.

Decision makers should understand that ozone depletion and global warming are two separate environmental issues, yet recognise that neither issue can be dealt with effectively in a vacuum of knowledge. There is also need to consider these issues to evaluate and select the options for non-ODS technologies.

14.2.1.1 Stratospheric ozone depletion

Decision makers in government and industry should have an adequate understanding of ozone depletion. This information is needed to develop policy, write regulations and to be able to answer the public's questions. It is important to note that there continues to be new measurements and new scientific findings with respect to ozone depletion. This should include data on UV-B ground level radiation along with what is known of its effects.

It should be noted that information is needed on how well the best current computer models correlate with measured atmospheric data.

14.2.1.2 Global warming

Information on global warming must be available to decision makers. Readers should be told the state of scientific understanding: a) what is understood very well, b) what is understood reasonably well, c) what climate change predictions are less certain, and d) the most serious uncertainties that need resolution. The difference between direct and indirect global warming effect should be well understood, along with the concept of Total Equivalent Warming Impact (TEWI). TEWI accounts for the direct and indirect effect of global warming. Accounting for only the GWP might lead to decisions that would be self-defeating both for the environment and the economy. TEWI results based on energy production structure and the integrated time horizon should be published and made widely available. Decision makers should be made aware that using short integration time horizons significantly discounts the impact of long-lived gases like carbon dioxide (CO_2).

Decision makers must have ready access to data on the direct effects of global warming. Data that is required includes the global warming potential (GWP) for CFCs and HCFCs and alternative refrigerants as well as the refrigerant leak rates from equipment. The GWP values for all commercially available refrigerants are well known. Information on refrigerant leak rates, however, needs to be constantly updated, as newer equipment is made progressively leak-free. Although ozone depletion and global warming are two separate phenomena, they are interrelated. Information on the interplay between these two effects should be made available.

In addition, the indirect effects (i.e. the effects of CO_2 emissions from powerplants that generate electricity required to run refrigeration equipment) need to be understood. This requires an understanding of the method in which electricity is generated for a locality, electricity transmission losses, and end-use equipment efficiency.

14.2.2 Refrigerant information

Decision makers need to be familiar with the alternative refrigerants that are available and how they compare with the CFCs they are replacing. This information can be used by regulators to decide which refrigerants are acceptable for certain applications. Accurate refrigerant information is needed by engineers to design new equipment and to modify existing equipment to accept alternative refrigerants. It will be necessary to understand the availability of refrigerants and to know how much of future refrigerant supply will be recycled vs. new production.

For each refrigerant, information is required on:

14.2.2.1 Thermophysical properties

Section 2 of this report addresses the need for information on thermophysical properties of refrigerants.

14.2.2.2 Safety information

Flammability and toxicity classifications are required, along with the particular risks and safety measures associated with each refrigerant. While this information is already available and disseminated for some of the alternative refrigerants (those recognised in ASHRAE Standard 34), it will also be necessary for every refrigerant and blend that comes to market. Information must be provided on the handling techniques so that flammable or toxic refrigerants can be safely utilised. The Alternative Fluorocarbon Environmental Acceptability Survey (AFEAS) has conducted extensive evaluations on toxicity and environmental effects of potential fluorocarbon alternatives. These data have been provided to UNEP and other public sources.

14.2.2.3 Material compatibility and lubricants

Decision makers have to know about material compatibility and details of oil behaviour. Information is therefore necessary on all types of materials, for every practical combination of refrigerant and lubricant that is under consideration for use.

14.2.2.4 Production and availability

Decision makers need to know what refrigerants are already available, in which countries, from which companies, as well as current and projected costs relative to the CFCs they will replace. They also need to know if potential demand and residual production will be sufficient for their needs. Developing countries must, above all, know where to buy CFCs during their 10-year grace period, including potential recovered CFCs.

14.2.2.5 Energy efficiency and operating characteristics

The energy efficiency and operating characteristics of each alternative refrigerant/lubricant pair should be evaluated and compared with other pairs. It is important that new refrigerants retain comparable efficiency and refrigeration capacity as the original refrigerant, especially in retrofit applications. Other operating characteristics, such as compressor discharge temperature, will have to be compared to those of the original refrigerant.

14.2.2.6 Refrigerant stability

Decision makers need to know the atmospheric lifetime of a refrigerant and what becomes of it after it is released into the atmosphere, in order to understand its environmental impact (i.e., on the ozone layer and on global warming or on the ecosystems) Likewise, designers need to understand the chemical stability of a refrigerant over the many years it is likely to remain in refrigeration equipment.

14.2.3 Information on vapour-compression refrigeration and A/C equipment

Information is needed on both existing installations and new equipment that is commercially available. This information is needed by policy makers to aid in planning a timely phaseout of ozone depleting substances (ODS). It is needed by building owners, designers, architects, engineers, facility managers, and service personnel to help them in their responsibilities of moving to alternative refrigerants.

14.2.3.1 Quantity of existing equipment to be replaced or converted

Decision makers need to know how many existing installations are involved and which equipment can be kept in operation via refrigerant recycling and which will have to be replaced or retrofitted. Such information is important to have an understanding of the consequences of government regulations, for equipment manufacturers to plan production, and so that an adequate installation and service infrastructure can be put in place.

14.2.3.2 Conservation techniques in existing equipment (servicing and maintenance)

It is important to disseminate information on good servicing and maintenance practices; recognising that about three quarters of CFC refrigerants are used to service older existing equipment and only one quarter is consumed to produce new equipment. This is especially important in prolonging the availability of existing refrigerants and the equipment dependent on them. Important in this area is training aimed at service personnel on the detection of refrigerant leaks.

14.2.3.3 Recovery, recycling and reclamation

Effective refrigerant recovery, recycling and reclamation are key components of an ODS phaseout scheme. In particular, service personnel need to be trained in the proper methods of refrigerant handling so that emissions are minimised. Information on existing standards for recovery, recycling and reclamation may be helpful. Service people need to know the contaminants to avoid and the procedures to follow. Additionally, there are numerous problems that can occur if refrigerants are cross contaminated which can make them unrecoverable and unusable. All nations should consider structuring a recovery and recycle infrastructure to ensure extending the useful life of existing CFC supplies.

The ability of recycled or reclaimed refrigerant to perform similarly to new refrigerant must be understood. For example, recycled refrigerants must not have an adverse effect on equipment reliability or life. Adequate reclaiming facilities must be available and service personnel should be aware of how to go about having refrigerants reclaimed.

14.2.3.4 New equipment

For new systems, the most urgent need is for data on the performance, cost, and availability of equipment using alternative refrigerants, such as HFC-134a, HCFC-123 and the various refrigerant blends which could replace CFCs. Information is needed on the leakage rates of equipment.

14.2.3.5 Retrofit (conversion) equipment

For retrofitting existing equipment, information requirements are similar to those for new equipment. Data on the alternative refrigerant's performance is urgently needed. Information is also required on conversion procedures, and in particular, specifications on material compatibility, lubricant performance, and other aspects of system operation. Information on the cost of a conversion is necessary, as well as on the availability of conversion equipment, in order to determine whether a retrofit would be appropriate.

14.2.4 "Not-In-Kind" refrigeration technology

"Not-in-kind" technology refers to air-conditioning and refrigeration equipment that does not use the traditional vapour compression Rankine cycle with fluorocarbon refrigerants. These systems range from vapour compression systems using non- fluorocarbons, to gas compression systems, to systems that do not involve any compression techniques. Some of these systems are commercially available, others are under development. Information on the performance of alternative technologies is required to evaluate their application range. The cost of alternative technology systems is an important factor which allows one to estimate how suitable a technology is in comparison with vapour compression systems.

14.2.5 Regulations

Decision makers need to be aware of the terms of the Montreal Protocol as well as all applicable national regulations. Likewise, building codes and product standards play an important part in deciding which equipment and refrigerants will be replace ODS.

14.2.6 Financing options

Manufacturing companies and financial institutions in both developing and developed countries must:

- be able to assess the financial consequences of the different solutions (retrofitting new equipment with intermediate refrigerants, long-term substitutes, etc.).
- be familiar with the financing possibilities, especially those provided for in the framework of the Multilateral Fund, and particularly:
    - where and how to present requests
    - the status and plans of the country program
    - how decisions are taken on requests.

14.3 Available information

This section further addresses the information requirements that were outlined in Section 14.2. It is aimed at alerting the reader as to what information is available to the decision maker. Some information needed to make decisions about the phaseout of ODS is available though computerised databases, some of which are broad in scope. Much of the needed information is available from government agencies as well as non-governmental organisations (NGOs).

14.3.1 Clearinghouses and databases

Three clearinghouses and databases specialising in alternative refrigerants and related information are described below. For more information, contact the organisations (see Section 14.3.2)

Air-Conditioning and Refrigeration Technology Institute (ARTI) Refrigerant Database

ARTI, under funding from the U.S. Department of Energy and the U.S. air-conditioning and refrigeration industry, offers a bibliographic database containing citations and synopses for related documents and publications of interest to the industry. The ARTI Refrigerant Database is issued via diskette with updates provided on a quarterly basis.

Data summaries on refrigerants and materials of construction are also included in the database. The key concentration areas are refrigerant-lubricant compatibility (e.g., compatibility with metals, plastics, elastomers, motor insulation, desiccants, and other materials), thermal and chemical stability of refrigerant-lubricant systems, and refrigerant-lubricant system properties (such as miscibility, solubility, viscosity, and lubricity). The effects of refrigerants and lubricants on heat transfer, system capacity and system efficiency also are emphasised. Environmental impact data, flammability, toxicity, and other safety information on refrigerants and associated lubricants are presented.

Technical reports from ARTIs Materials Compatibility and Lubricants Research (MCLR) Program as well as ARIs HCFC-22 Alternative Refrigerants Evaluation Program (AREP) are referenced in -- and are available through -- the database.

United Nations Environmental Programme (UNEP) OzonAction Information Clearinghouse [OAIC]

OAIC offers a range of communication media suitable to the users' technical and cost constraints. It is designed to cater to the varying needs of more than 100 developing countries. Information on phaseout activities, technical abstracts, policies, calendar events, expert contact data, news bulletins, purchasing information on technologies, products and services is disseminated through hard copies as well as through an on-line computerised system. It operates a query-response service on technical programmatic queries. The computerised component is an electronic bulletin board system that provides the user with all above information and electronic mail capability to communicate with each other and helps UNEP's query response service. The on-line system is accessible by anyone with a personal computer, a modem, communication software and access to a telephone line.

'Protecting the ozone layer' Volume 1 on "Refrigerants", is an easy to understand technical document for decision makers in government and industry as well as for technical managers. It provides options available for alternatives.

Technology catalogues for ODS-free technology in refrigeration and air-conditioning gives contact information on alternative technologies, products and services as well as providing aid to enhance the options.
The clearinghouse also provides a series of informational papers, training manuals and case studies.

The services of UNEP's Industry and Environment/Programme Activity Centre (IE/PAC) are available for free to developing countries.

International Institute of Refrigeration's (IIR) FRIGINTER and FRIGDOC

Over 300 journals, published in 20 different languages, are examined regularly by IIR specialists. 600 articles are selected, analysed, and published in a bi-monthly bulletin. They are classified by subjects such as refrigerants, thermodynamics and heat transfer; refrigerating machinery; air conditioning; heat pumps and energy recovery; refrigerated transport; cryology, food science and technology, and economics, education and regulations. The bulletin forms the base for the IIR's computerised databases accessible through FRIGINTER and FRIDOC. FRIGINTER is an off-line service, used by the IIR staff to respond to particular enquiries. FRIDOC is available on floppy disks (sent to subscribers every two months). FRIDOC is a bi-monthly, updated database that has covered the whole field of refrigeration since 1982. It contains 40,000 references, and grows by 4,000 new references every year. Any information, from basic data to technical and economic information, can be obtained through a keyword interrogation. An author interrogation is also possible. Every reference consists of a summary, together with the title, the list of associated key words, and the source of the publication, which is available at the IIR.

14.3.2 Other information sources

Information that is needed to help phaseout ODS is available from a wide variety of sources around the world. Non-governmental organisations (such as industry trade associations, industry professional societies, refrigerant producers, and equipment manufacturers) have taken a proactive role in preparing material on alternative technology. A partial list of some of those sources follows.

AFRICA

Burkina-Faso
Association des Ingénieur et
Techniciens Frigoristes du
Burkina (AITFB)
B.P. 7047, Ouagadougou

Egypt
Egyptian Society of Engineers
Society of Mechanical
Engineers
28, Ramses Street
Cairo
P: +20-2-5741290
F: +20-2-5740569

Morocco
Association Nationale du Froid
B.P. 6433
Rabat-Instituts
Rabat

South Africa
AECI (CAP) Limited
PO Box 1122
Carlton Centre
Johannesburg 2000
South Africa
P: +27-11-223-9113
F: +27-11-223-2172/1781

The South African Institute of
Refrigeration and Air
Conditioning
P.O. Box 175, Isando
Transvaal 1600
P: +27-11-8862555
F: +27-11-8865723

ASIA

China

China Committee of HVAC
P.O. Box 752
Beijing 100013
China
P: +86-1-4211133
F: +86-1-4221369

China Refrigeration and Air
Conditioning Industry
Association (CRAA)
No. 77 Bei Li Shi Street
Westernt
Beijing
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F: +86-1-834-3502

Chinese Association of
Refrigeration.
Zhong Zhou Refrig. Corp.
Bldg. 11, South No. 1 Lane
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Beijing, 100045
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F: +86-1-8536262

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India

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Refrigeration Association
4 Pho House, Siri Fort
Institutional Area
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14.4 Disseminating the information

Information provided cannot always be disseminated 'as it is.' First, information has to be reliable and up-to-date. Second, it should discuss existing technical options, technology suppliers, cost-benefits and global sources of financial and technical assistance. Promotional information, while very useful for the user in some cases, may lead to selecting an option which may not be the 'best' for a given situation. Further, the relevant information needed may vary depending on large or small user. The processing of information would include compilation, formatting, cataloguing, condensing, abstracting and simplifying. It is needed to be provided in easy to understand and digestible language. This is specifically true in the case of developing countries.

14.4.1 The audience for this information

It is important that the information needs of decision makers be considered. This section examines the audience and how it might use the information listed in the previous sections.

The decision maker needs information for:

a) the development or procurement of alternative products and services;
b) better management of refrigerant conservation, containment, and recovery or recycling;
c) making a cost effective equipment decision;
d) establishing policy with respect to encouraging switching to other efficient equipment options
e) conducting training, awareness raising and general education on the various issues.

14.4.1.1 Government agencies

National ozone units, focal points in the government of all countries need, information on ODS and alternatives in order to make informed decisions regarding their governments' policies, regulations, and standards. Government agencies that deal with the environment, commerce, and international treaties all need to be aware of atmospheric findings, the state of ODS phaseout, and the implications upon their country. Many government officials formulating policy do not have a technical background. Information that is made available to these officials must reflect this.

14.4.1.2 Manufacturers/Service personnel

Many individual manufacturers are impacted by information relating to the replacement of CFCs. Some companies may not even be aware that they are affected. The obvious companies are those directly involved in manufacturing refrigerant and equipment, and those that provide components to these industries. These companies have many ways of obtaining the data they need. A second tier of companies is associated with industries that incorporate refrigeration, air conditioning, and heat pump equipment into their product line including vehicle manufacturers, residential, commercial, and industrial builders, process designers in all major industries, stores and transport companies. A third tier of companies is represented by the service industry that repairs, maintains, and replaces equipment. Information flow to these second and third tier companies is not always straightforward and extra efforts have to be made to ensure that they receive the information that they need. Additional companies in almost all sectors of the world economy are also indirectly impacted by the need for information about CFC alternatives. An example is financial institutions that provide the loans for the construction of new capital equipment.

14.4.1.3 Teaching institutions

Teaching institutions require a broad range of information depending on their role in society. Research-oriented institutions require information on the characteristics of proposed alternative technologies and refrigerants, as well as the more current research results and planned activities of other research and development organisations. Education-oriented institutions (trade school government-run teaching programs, and correspondence teaching programs) need information pertaining to system designs, chemical and toxicological data, etc. Training institutions need information on the latest and best practices associated with operations, maintenance, recycling, conservation, and other aspects of refrigeration system performance.

14.4.1.4 Professional societies and industry associations

Societies and associations need information to further disseminate to their member companies and experts. Such associations are centres for holding seminars, publishing bulletins and technical literature's through journals. Associations in developed and developing countries also need to know about each other to exchange information.

14.4.1.5 Researchers

Researchers working in this field require the most timely and accurate data. They receive data from technical papers, databases, and from personal interaction with other researchers. Developing countries represent vast number of technical and scientific man-power, working in universities and private institutes. They are in need of information on frontiers of technology to ensure that their programs benefit from the existing knowledge base. The information provided to them may catalyse the co-operation between research institutes in developed and developing countries.

14.4.1.6 Users and general public

Public opinion and attitudes shape government policy and product development decisions by industry. The general public needs to be informed about the energy and environmental impacts, safety considerations, reliability, initial costs and operating costs associated with the use of the competitive refrigeration technologies, and the alternatives that are available to them.

14.4.1.7 Implementing Agencies under the Multilateral Fund of the Montreal Protocol and their review committees

The World Bank, UNIDO and UNEP are the implementing agencies assisting Article 5(1) developing countries to phaseout ODS. Their activities involve training, demonstration, feasibility studies and investment projects. Consultants/experts involved in formulation of the projects need up-to-date and global information on the phaseout options.

14.4.1.8 Secretariat of the Multilateral Fund

The projects formulated and reviewed by experts working for the implementing agencies are submitted to the Secretariat of the Multilateral Fund for the further recommendation to the Executive Committee who approves the Fund for the project. It is necessary that the Secretariat of the Multilateral Fund is well informed on the latest technology and policy trends.

14.4.1.9 Non-Governmental Organisations (NGOs)

NGOs need information to devise their own awareness campaigns. A network of NGOs would be an effective way to further disseminate this information. NGOs play a major role in creating awareness among end-users. They also form key linkages between users and policy makers in government and industry. They need reliable, global information to design campaigns. NGOs also work at the local levels and can play an effective role in implementation at good practices in the servicing and maintenance sector which is scattered. NGOs would also need information on not-in-kind technologies to devise their out-reach activities.

14.5 Research underway

This section addresses research which is underway and provides information that will help research results become widely disseminated. The information for this section was obtained through a survey of researchers throughout the world. However, the accompanying information is not to be construed as an exhaustive accounting of on-going research efforts in the air-conditioning and refrigeration sector. There are numerous programs and individual projects that are funded by other interested stakeholders that are not included in this survey. Additionally, research within private manufacturing firms is not publicly available. Finally, research that was previously started and subsequently completed or terminated is not reported here. It is anticipated that, by the time this document becomes publicly available, previous work will already have manifested itself into equipment designs that soon will be available on the world markets. Hence, the investigations noted within this section are meant to be representative of the types of research that are ongoing to satisfy the needs of equipment manufacturers, users and service personnel.

As indicated in section 14.2, there are a multitude of issues that need to be identified, quantified, and analysed prior to successfully phasing out of ozone depleting substances. For air-conditioning and refrigeration equipment applications, refrigerant concerns are related to thermophysical properties, materials compatibility, safety, and, of course, environmental impacts. Related equipment considerations focus on energy efficiency, performance, conversion requirements, and technology options. There are many organisations around the world that are involved in developing and/or supporting research on air-conditioning and refrigeration equipment and their working fluids. These organisations include private equipment manufacturers, chemical producers, industry trade associations, industry professional societies, governmental agencies and laboratories, and local governments. Additionally, these entities provide significant funding and in-kind support to many private and university research facilities for the furtherance of the investigations.

Most investigations are funded and performed within one country. However, various activities are of mutual interest and the work is performed on an international basis, or with significant collaboration among researchers in multiple countries.

The technology transfer is not complete until the technology is adapted by the user. Research and developmental efforts are required in order to assist developing countries in adapting to the technologies. The Multilateral Fund, established to assist developing countries, recognises such activities as one of the elements of incremental costs.

14.5.1 Alternative refrigerant research

Much attention has been placed on identifying and evaluating potential alternative fluids to replace ozone depleting refrigerants. Early work was concerned with the screening of compounds that could serve useful roles as refrigerants. Investigations, experimental and modelling, have evaluated single, binary, ternary and even more complex mixtures to ascertain their performance and safety trade-offs. Once a compound or blend is identified as a candidate for a particular application, it needs to be synthesised so that various investigations can be performed.

With the multitude of pure components and mixtures that have been identified as potential refrigerants, the need for thermophysical data has intensified in the past few years. Now that CFC-11 and CFC-12 have satisfactory long-term replacements, the immediate need is in identifying replacements for HCFC-22 and R-502. Since HCFC-22 is the dominant refrigerant used in air-conditioning equipment on a world-wide basis (R-502 is composed of 49% HCFC-22 and 51% CFC-115), much of the on-going thermophysical research is on HCFC-22 alternatives. This thermophysical research is geared towards general understanding of the property-based behaviour of the molecular structure and in revealing the unknown property behaviour of fluids applied in various engineering applications. Refer to Table 14.1 for representative examples of on-going research.
In addition to thermophysical property work there are numerous research programs geared towards evaluating alternative working fluids; man-made (refer to Table 14.2) and natural (refer to Table 14.3). Characterisation of heat transfer mechanisms (refer to Table 14.4) and ascertaining compatibility with materials (refer to Table 14.5) are also well underway.

14.5.2 Energy efficiency research

Another large area of interest is in establishing the operating attributes of numerous candidate fluids in specific applications. Various research programs are seeking to establish the impact alternative fluids will have on efficiency, capacity, and overall reliability of existing equipment. Referring to Table 14.6, it can be seen that this is an international effort.
At the same time, much effort is being expanded to improve the energy efficiency of new equipment (refer to Table 14.7) or to investigate alternative cycles that use *not-in-kind* technologies (refer to Table 14.8).

Table 14.1 Thermophysical property investigations

Funding Organisation	Research Project Title [Research Organisation]	Research Objective	Start - Compl.	Contact person & phone no.
Governmepts of Austria / Canada/ Germany/Japan/ Norway/Sweden/UK/USA (* : Phase 1 only)	Annex 18 of the IEA Heat Pump programme: "Thermophysical Properties of Environmentally Acceptable Refrigerants"	Phase I: Properties research of CFC alternatives Phase II: Properties research of HCFC alternatives	1989-1993 1993-1996	Operating Agent: Dr. Mark McLinden US Department of Commerce, NIST 325 Broadway Bldg 2, MS 584-03 Boulder, CO 80303-3328 USA p. 001- 303 497 3580 f. 00 1- 303 497 5224
UK Department of Trade and Industry	IUPAC Thermodynamic Tables	Extend existing computer package for predicting mixture properties to include the alternative refrigerants, where very accurate equations of state are used for the pure components.	on-going	K.M. de Reuck Project Centre Department of Chemical Engineering Imperial College London SW7 2By UK p. (44) 171 59 45616
DFG (Deutseke Forschurgs-Gemeiusdge) Chemicals & Polymers	Thermodymanic Properties of CFC-substitutes HCFC-124 and HFC-134a	Investigation of thermodymanic properties of HCFC-124 and HFC-134a pvt-data, EOS, vapour pressure)	2/92-2/94	Dr. Bernd de Vries Universität Hannover Institutut für thermodynamik Callinstrabe 36 30167 Hannover 1 GERMANY p. 49 511 762 4601 f. 49 511 762 3857
Swedish Council for Building Research (BFR)	Thermodynamic Properties for Secondary Refrigerants [Applieo Thermodynamics and Refrigeration, The Royal Institute of Technology; Stockholm, Sweden]	To evaluate suitable fluids for indirect refrigerating systems and to provide tables and charts for properties.	1991-1994	Åke Melinder p. 46 8 790 7454
U.S National Institute of Standards and Technology (NIST)	Database 23: Thermodynamic Properties of Refrigerants and Refrigerant Mixtures (REFPROP)	Comprehensive thermodynamic and transport properties of a wide variety of alternative refrigerants and refrigerant blends; program includes experimental measurements, theoretical and modeling studies.	1982-on-going	Dr. Mark McLinden US Department of Commerce, NIST 325 Broadway Bldg 2, MS 584-03 Boulder, CO 80303-3328 USA p. 001- 303 497 3580 f. 001- 303 497 5224
BMFT (Federal German Ministry of Research and Technology)	Database: Thermophysical Properties of Alternative Refrigerants	Development of a database; Evaluation of data and equations: thermophysical and environmental properties of alternative refrigerants, including HCFCs	1/93-12/94	Dr. R. Krauss Universität Stuttgart Institut fur Thermodynamik und Wärmetechnik Pfaffenwaldring 6 7000 Stuttgart 80 GERMANY p. 49 711 685 6108 f. 49 711 685 3503

Table 14.2 Research on non-CFC refrigerants

Funding Organisation	Research Project Title [Research Organisation]	Research Objective	Start - Compl.	Contact person & phone no.
Deutsche Bundesstiftung Umwelt/Industry	Retrofit procedures of existing CFC refrigeration plants to environmentally benign refrigerants (Retrofit)	Replacement of CFCs in refrigeration equipment by environmentally benign alternatives	3/93 - 3/94	Dipl. Ing. K. Beermann p. 49 511 762 5202
Association of Home Appliance Manufacturer (AHAM)	Appliance Industry/Government CFC Replacement Consortium (ARC), Inc. [30 Appliance Manufacturers and Supplier Members, DOE, EPA, ARI, and EPRI]	Perform the research necessary to identify environmentally benign, cost effective replacements for CFC-11 in foam insulation and CFC-12 in refrigeration systems (24 projects, 12 complete)	3/89-on-going	Leonard J. Swatkowski, Jr. AHAM 20 North Wacker Drive Chicago, IL 60606 USA p. 1 312 984 5800 f. 1 312 984 5823
Indian Institute of Technology (IITD)	Studies on substitutes to CFC-12 in transport refrigeration	Simulation and Experimental studies on uses of mixtures of Non-CFC refrigerants in large capacity refrigeration and air-conditioning systems	1/92-6/95	Professor R.S. Agarwal Indian Institute of Technology-Delhi New Delhi 110016 INDIA p. 91 11 686 5279 f. 91 11 686 2037
Forschungsrat Kältechnik (FKT)	Blends for substitution of HCFC-22, R-502, and R13B1		4/94-4/95	Dr. K. Jahn Forschungsrat Kältechnik Postfach 710 864 60498 Frankfurt GERMANY p. 49 69 660 3277 f. 49 69 660 3218
17-Company Consortium	Air Conditioning and Refrigeration Center [University of Illinois at Urbana-Champaign]	Refrigerant properties; Fundamentals of heat transfer, frost, friction & wear etc.; Component design; system optimisation	1989-	Professor Clark W. Bullard University of Illinois at Urbana-Champaign 144 Mechanical Engineering Bldg. 1206 West Green Street Urbana, IL 61801 USA p. 001 217 333 7734 f. 001 217 244 6534

Table 14.2: Research on non-CFC Refrigerants (con't)

Funding Organisation	Research Project Title [Research Organisation]	Research Objective	Start - Compl.	Contact person & phone no.
U.S. EPA	Modeling Evaluation of HCFC-22 Replacement Blends [Research Triangle Park]	Computer modeling and evaluation of binary and ternary mixtures as potential replacements to HCFC-22 in heat pumps.	4/93 - 8/94	Robert Hendriks U.S. Environmental Protection Agency AEERL/MD-623B Research Triangle Park, NC 27711 USA p. 001 919 541 3928 f. 001 919 541 7885
BMFT Federal German Ministry of Research and Technology	Reduction of CFC Emissions in Refrigeration and Air-Conditioning in Germany Coordination: DKV (German Society for Refrigeration and Air-Conditioning; Deutscher Kälte- und Klimatechnischer Verein e. V.) Execution: 15 German Research Institutions and Industries	Development and demonstration of ecologically and toxicologically acceptable refrigerants and technologies for the replacement of fully and partly halogenated CFCs	7/89-6/93 --- follow-up projects: 94-95	Hans Jurgen Laue Heat Pump & Air Conditioning Information Center FIS - GmbH D-7514 Eggenstein-Leopoldshafen 2 GERMANY p. 49 7247 808 350 f. 49 7247 808666
Governments of Belgium, Japan, The Netherlands, Norway, Switzerland	Annex 20 of the IEA Heat Pump programme: "Working Fluid Safety"	As assessment of the safety implications of more than 160 working fluids, including hydrocarbons and ammonia.	1990-1993 will publish in mid 1994	Operating Agent: Prof. Jan Berghmans Katholieke Universiteit Leuven Instituut Mechanica Celestijnenlaan 300A B-3030 Heverlee BELGIUM p. 32 16 28 6611 f. 32 16 22 2345
Forschungsrat Kältechnik (FKT)	Safety of Refrigerating With Ammonia		7/93-12/94	Dr. K. Jahn Forschungsrat Kältechnik Postfach 710 864 60498 Frankfurt GERMANY p.49 69 660 3277 f. 49 69 660 3218
European Economy Community	Replacement of CFCs in Refrigeration Equipment by Environmentally Benign Alternatives	Oil behaviour of possible substitutes for refrigerants HCFC-22 and R-502	1/93-4/95	Dipl. -Ing M. Burke p. 49 511 762 2538

Table 14.3 Research on "natural refrigerants"

Funding Organisation	Research Project Title [Research Organisation]	Research Objective	Start - Compl.	Contact person & phone no.
The Foundation for Scientific and Industrial Research at the Norwegian Institute of Technology (NTH-SINTEF)	CFC-free technology for heat pumps and refrigeration plants	Produce basic knowledge and results within efficient and environmental friendly CFC-free technology for heat pumps and refrigeration plants, with focus on "natural refrigerants" (carbon dioxide, ammonia and hydrocarbons)	1993-1997	Petter Nekså SINTEF Refrigeration Engineering N-7034 Trondhelm NORWAY p. 47 73 593923 f. 47 73 593926
NTH-SINTEF	"Natural refrigerants" in heat pumps and refrigeration plants	Develop systems with carbon dioxide as the working fluid in heat pumps and refrigeration plants	1993-	Gustav Lorentzen p. 47 73 593899 Jostein Pettersen p. 47 73 593924 SINTEF Refrigeration Engineering N-7034 Trondhelm NORWAY f. 47 73 593926
Research Association of the Austrian Utilities	CO_2 - A Refrigerant for Heat Pumps (Institute of Thermal Engineering, Graz University of Technology, Austria)	Based on investigations of the transcritical CO_2-cycle carried out by G. Lorentzen, SINTEF, Norway, possible applications of CO_2 in heat pumps with 10 to 100kW thermal output are being investigated.	1994 - 1997	Dr. Hermann Halozan Dept. of HVAC Institute of Thermal Engineering Graz University of Technology Inffeldgasse 25 A-8010 Graz AUSTRIA p. 43 316 873 7303 f. 43 316 873 7305
Governments of the majority of countries participating in the IEA Heat Pump programme	Proposed: Annex 22 of the IEA Heat Pump programme: Vapour Compression Systems with Ecologically Safe Working Fluids (pending)	To establish design criteria for the operation of vapour compression systems with ammonia, carbon dioxide, water, propane, butane, and mixtures of propane and butane; and to evaluate present state of the art experiences with these refrigerants	1994 - 1996	Operating Agent: Rune Aarlien SINTEF Refrigeration Engineering Kolbjørn Hejes Veg I D 7034 Trondheim NORWAY p. 47 73 593 900 f. 47 73 593 926

Table 14.3: Research on "Natural Refrigerants" (con't.)

Funding Organisation	Research Project Title [Research Organisation]	Research Objective	Start - Compl.	Contact person & phone no.
Swedish Board for Industrial Development (NUTEK)	Applications of Environmentally Friendly Fluids as Refrigerants [Applied Thermodynamics and Refrigeration, The Royal Institute of Technology; Stockholm, Sweden]	To investigate the use of natural fluids (such as ammonia and hydrocarbons) in refrigeration and heat pumps and problems associated with such use.	1994 - 1996	Professor Eric Granryd The Royal Institute of Technology S-100 44 Stockholm SWEDEN p. 46 8 790 7452 f. 46 8 203 007
Entre per Le Nuove Tecnologie, L'Energia E L'Ambient (ENEA), Merloni Termo Sanitari (MTS) Italian Gas Utility (ITAL GAS), French Gas Utility (GAZ de France)	Development of an advanced heat pump, using NH_3/H_2O with high energy performance.	Develop an advanced absorption heat pump for heating, cooling and sanitary hot water production, to be used in Central and South Europe.	7/93 - 12/95	Paolo Giacometti ENEA Cre-Casaccio via Anguillarese 301 00060 S. Maria di Galeria ROME p. 39 5 3048 3089
National Research Council (NRC) and Environment Canada	"Natural Refrigerants" [NRC]	Evaluate the performance of "natural refrigerants" in vapour compression cycles.	1995 -	Keith Snelson National Research Council Canada Ottawa, Ontario CANADA p. 613 993 4892 f. 613 954 1235
U.S. DOE	Thermally-Activated Heat Pump Program: Commercial Gas Cooling [York International]	Develop and commercialise highly efficient large commercial absorption chillers using advanced cycles with LiBr/water as the working fluid.	1992- 1996	Ronald Fiskum U.S. Department of Energy Forrestal Building 5H-048, Mail Stop EE-422 1000 Independence Ave., SW Washington, DC 20585 USA p. 001 202 586 9130 f. 001 202 586 1628

Table 14.4 Heat transfer research

Funding Organisation	Research Project Title [Research Organisation]	Research Objective	Start - Compl.	Contact person & phone no.
Forschungsrat Kältechnik (FKT)	Heat transition, of HFC-32, HFC-143a, and HFC-125 during boiling process		3/94 - 12/94	Dr. K. Jahn Forschungsrat Kältechnik Post fach 710 864 60498 Frankfurt GERMANY p. 49 69 660 3277 f. 49 69 660 3218
Governments of Canada/The Netherlands/ Norway/ Sweden/Switzerland/USA	Annex 17 of the IEA Heat Pump programme: "Experiences with new Refrigerants in Evaporators."	As assessment of the behaviour of HFC-134a, HFC-152a and HCFC-22 in evaporators - An international experimental review of heat transfer and pressure drop correlations.	1990 - 1992; will publish in mid-1994	Operating agent: Professor Thore Berntsson Chalmers University of Technology 412 96 Gothenburg SWEDEN p. 46 31 772 3009 f. 46 31 82 1928
U.S. National Science Foundation (NSF)	The Falling Film Mode: Its Transitions Hysteresis, and Effect on Heat Transfer [University of Illinois]	Understanding the falling film mode and its impact on heat transfer in chiller evaporators	8/92 - 3/94	Anthony M. Jacobi University of Illinois at Urbana-Champaign 1206 West Green Street Urbana, IL 61801 USA p. 001 217 333 4108 f. 001 217 244 6534
Swedish Council for Building Research (BFR)	Flow Boiling of Pure and Oil Contaminated Refrigerants (Ph.D. Thesis) [Applied Thermodynamics and Refrigeration, The Royal Institute of Technology; Stockholm, Sweden]	Investigation of heat transfer and pressure drop in evaporation of pure HFC-134a and HCFC-124a with various oils in a horisontal tube.	1988 - 1993	Dr. Katarina Hambraeus The Royal Institute of Technology Stockholm SWEDEN p. 46 8 790 7451 f. 46 8 20 30 07
Swedish Council for Building Research (BFR)	Heat Transfer in Flow of Zeotropic Refrigerant Mixtures [Applied Thermodynamics and Refrigeration, The Royal Institute of Technology; Stockholm, Sweden]	Investigate heat transfer phenomenon in flow boiling of zeotropic refrigerant mixtures.	1990 - 1995	Dr. Wei Shao The Royal Institute of Technology Stockholm SWEDEN p. 46 8 790 8642 f. 46 8 20 30 07

Table 14.4: Heat Transfer Research (con't)

Funding Organisation	Research Project Title [Research Organisation]	Research Objective	Start - Compl.	Contact person & phone no.
Electric Power Research Institute (EPRI)	Alternative Refrigerants Evaluation Program (AREP) [University of Illinois, Iowa State, Lehigh University]	Measure and correlate refrigerant heat transfer coefficients (for evaporation and condensation) to accelerate development of equipment using HCFC-22 and R-502 substitutes.	11/92 - 4/94	Dr. Sehkar Kondepudi Electric Power Research Institute 3412 Hillview Avenue Post Office Box 10412 Palo Alto, CA 94303 USA p. 001 415 855 2131 f. 001 415 855 2954
Swiss Federal Office of Energy (BEW) and American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE)	Evaporation of New Refrigerants on tubes with enhanced surfaces		thru 12/95	Prof. Dr. D. Favrat Laboratoire d'Energétique Industrielle p. 41 21 693 2511

Table 14.5 Materials compatibility research

Funding Organisation	Research Project Title [Research Organisation]	Research Objective	Start - Compl.	Contact person & phone no.
Gas Research Institute (GRI)	Commercial Heat Pumps	Materials research for improved ammonia heat pump application.	1991 - 1996	Gary Nowakowski Gas Research Institute 8600 W. Bryn Mawr Ave. Chicago, IL 60631 USA p. 001 312 399 8249 f. 001 312 399 8170
U.S. Department of Energy (DOE) and Air-Conditioning and Refrigeration Institute (ARTI)	Materials Compatibility and Lubricants Research (MCLR) Program [~40 separate contracts]	Provide materials compatibility testing information on alternative refrigerants and lubricants; measure refrigerant thermophysical properties; and provide research results on related issues. A data collection and dissemination effort is also included.	9/91 - 9/97	Steve Szymurski ARTI 4301 North Fairfax Drive, Suite 425 Arlington, VA 22203 USA p. 001 703 524 8800 f. 001 703 524 6351

Table 14.6 Performance of alternative refrigerants in existing equipment

Funding Organisation	Research Project Title [Research Organisation]	Research Objective	Start - Compl.	Contact person & phone no.
Forschungsrat Kältechnik (FKT)	Tests of blends in compressors		94/95	Dr. K. Jahn Forschungsrat Kältechnik Post fach 710 864 60498 Frankfurt GERMANY p. 49 69 660 3277 f. 49 69 660 3218
U.S. Army	Thermodynamic Performance of Refrigeration Equipment with Alternative Refrigerants	Performance testing of alternative refrigerants	10/93 - 8/94	Dr. William Stewart University of Missouri - Kansas City 105 Mechanical Engineering Building 5605 Troost Kansas City, MO 64110 USA p. 001 816 235 1283 f. 001 816 235 1260
Department of the Environment, UK	Site trial of HFC-based alternative to HCFC-22 [Building Research Establishment (BRE)]	Investigate the practicality of a 'drop-in' conversion (retaining original lubricant and no hardware changes) of a small packaged HCFC-22 chiller to an HFC-based alternative, and carry out detailed performance assessment.	4/93 - 6/94	David Butler Building Research Establishment Garston Watford WD2 7JR p. 44 0923 664763 f. 44 0923 664095
Foundation for Research Science & Technology (FRST)	CFC-free Food Refrigeration [Massey University (Palmerston North) University of Otago(Dunedin)]	Test alternative refrigerants in industry-based refrigeration systems	7/92 - 6/95	Terry Chadderton Refrigeration and Energy Meat Industry Research Institute of New Zealand (MIRINZ); p. 7 855 6159 f. 7 855 3833

Table 14.6: Performance of Alternative Refrigerants in Existing Equipment (con't.)

Funding Organisation	Research Project Title [Research Organisation]	Research Objective	Start - Compl.	Contact person & phone no.
Department of Energy Research Fund (EFP)	Indirect system of refrigeration using CFC and HCFC-free refrigerant	Analyzing of COP for indirect systems. Develop component to be used in indirect systems (Controls, Heat exchangers, Pumps)	4/94 - 12/96	Dr. Per O. Danig Refrigeration Laboratory Technical University of Denmark Building 402-B DK 2800 Lyngby DENMARK p. 45 42884622 f. 45 45935215
Air-Conditioning and Refrigeration Institute (ARI)	Alternative Refrigerant Evaluation Program (AREP) [over 30 equipment manufacturing companies in North America, Japan and Europe]	Provide preliminary performance information (compressor calorimeter, drop-in, soft-optimised tests) on alternative refrigerants to HCFC-22 and R-502.	1/92 - 9/94	Dave Godwin ARI 4301 North Fairfax Drive, Suite 425 Arlington, VA 22203 USA p. 001 703 524 8800 f. 001 703 524 6351
Japan Refrigeration & Air-Conditioning Industry Association (JRAIA)	Japan Alternative Refrigerant Evaluation Program (JAREP) [12 equipment manufacturing companies in Japan]	Provide preliminary performance information (compressor calorimeter, drop-in, soft-optimised tests) on alternative refrigerants to HCFC-22 and R-502.	1/92 - 9/94	Keisuke Tachibana JRAIA Kikai Shinko Bldg. , 5-8 Shibakown 3-Chome Minato-ku, Tokyo 105 JAPAN p. 81 3 3432 1671 f. 81 3 3438 0308
EPRI/ U.S. EPA	Testing of Environmentally Safe Refrigerants/ Refrigerant Mixtures in Heating and Cooling Equipment [University of Maryland]	Test alternative refrigerants to HCFC-22 for unitary heat pumps, evaluate their relative performances, and investigate cycle modifications to maintain heat pump efficiency and performance.	7/92 - 9/94	Wayne Krill Electric Power Research Institute 3412 Hillview Avenue P.O. Box 10412 Palo Alto, CA 94303 USA p. 001 415 855 1033 f. 001 415 856 6621 Robert Hendriks U.S. Environmental Protection Agency AEERL/MD-62B Research Triangle Park, NC 27711 USA p. 001 919 541 3928 f. 001 919 541 7885
U.S. EPA	Improving Air-Conditioner and Heat Pump Performance with HCFC-22 Replacement Refrigerants [pending]	Improvement of hardware and systems to improve performance with HCFC-22 alternatives. Emphasis on retrofit systems.	9/93 - 9/96	Robert Hendriks U.S. Environmental Protection Agency AEERL/MD-62B Research Triangle Park, NC 27711 USA p. 001 919 541 3928 f. 001 919 541 7885

Table 14.7 Energy efficiency investigations

Funding Organisation	Research Project Title [Research Organisation]	Research Objective	Start - Compl.	Contact person & phone no.
U.S. DOE	Domestic Refrigerators [Oak Ridge National Laboratory (ORNL)]	Provide the technology base for the appliance industry to develop and introduce domestic refrigerator-freezers with 50% lower energy use than current models.	9/91 - 6/95	Phillip Fairchild ORNL Energy Division, Building 3147, MS 6070 P.O. Box 2008 Oak Ridge, TN 37831-6070 USA p. 001 615 574 2020 f. 001 615 574 9338
Agency of Industrial Science and Technology/ Ministry of International Trade and Industry (AIST/MITI) Japan	Broad Area Energy Utilisation Network System Technology (NEDO, New Energy and Industrial Technology Development Organisation)	Develop technologies required for realising an environmentally harmonised society capable of realising regeneration and recycling of energy as well as effective utilisation of available energy resources.	1993 - 2000	Teruaki Masuma New Energy and Industrial Technology Development Organisation (NEDO) Sunshine 60 Bldg., 29F 1-1, Higashi Ikebukuro 3-chome Toshima-ku, Tokyo 170 JAPAN p. 81 3 3987 9431 f. 81 3 5992 5233
New Energy and Industrial Technology Development Organisation (NEDO) & Ministry of International Trade and Industry(MITI) Japan	Follow up research on super heat pump energy accumulation system. (Ebara Co., Ltd., Kyushu Electric Co., Ltd., Chyubu Electric, Co. Ltd.)	Widening of application temperatures of HFC and HCFC super heat pumps to cooling condition and actual field tests. (Final Report of Super Heat Pump Project -1985-1993 is available)	4/94 - 3/96	Mr. Tsunoda New Sunshine Promotion HQ Agency of Industrial Science and Technology Ministry of Int'l Trade & Industry 1-3-1 Kasumigaseki, Chiyoda-bu Tokyo 100 JAPAN p. 3 3501 9471 f. 3 3501 9489 Mr. Masuma NEDO p. 81 3 3987 9431 f. 81 3 5992 5233 Dr. Akira Yabe AIST, MITI 1-2 Namiki Tsukuba Science City Ibaraki 305 JAPAN p. 81 298 58 7243 f. 81 298 58 7240

Table 14.7: Energy Efficiency Investigations (cont'd.)

Funding Organisation	Research Project Title [Research Organisation]	Research Objective	Start - Compl.	Contact person & phone no.
New Energy and Industrial Technology Development Organisation (NEDO) & Ministry of International Trade and Industry(MITI) Japan	Broad Area Energy Utilisation Network System -- Eco-energy City Concept (Large scale project of New Sunshine Program)	Main purpose is to realise the long distance energy transportation of waste heat from factories by use of chemical reactions. But includes new HFC refrigerants screening and experiments for compression-absorption cycles.	4/93 - 3/01	Mr. Yoshimura New Sunshine Pomotion HQ Agency of Industrial Science and Technology Ministry of International Trade and Industry (MITI) 1-3-1 Kasumigaseki, Chiyoda-bu Tokyo 100 JAPAN p. 3 3501 9471 f. 3 3501 9489 Dr. Akira Yabe AIST, Ministry of International Trade and Industry (MITI) 1-2 Namiki Tsukuba Science City Ibaraki 305 JAPAN p. 81 298 58 7243 f. 81 298 58 7240
Agency of Natural Resources & Energy (ANRE-MITI)	Unused Energy Utilisation Project (NEDO)	Develop technology for construct ideal district heating & cooling system utilising natural heat or waste heat	10/91 - 3/99	Naoyuki Haraoka (ANRE) p. 81 3 3501 3547
U.S. EPA	Use of Non-Chlorine Refrigerants and Refrigerant Mixtures in Heat Pumps and Air-Conditioning [pending]	Investigations of component and system options to improve performance with new refrigerants. Emphases on new designs.	9/93 - 9/96	Robert Hendriks U.S. Environmental Protection Agency AEERL/MD-62B Research Triangle Park, NC 27711 USA p. 001 919 541 3928 f. 001 919 541 7885
U.S. DOE	New Refrigerant [NIST, ORNL]	Provide the technology base for industry's switch to new refrigerants while increasing energy efficiency in building equipment	on-going	William Noel U.S. Department of Energy Forrestal Building 5H-048, Mail Stop EE-422 1000 Independence Ave, SW Washington, DC 20585 USA p.202/586-5335 f. 202/586-1628

Table 14.8 Alternative cycle investigations

Table 14.8: Alternative Cycle Investigations				
Funding Organisation	**Research Project Title [Research Organisation]**	**Research Objective**	**Start - Compl.**	**Contact person & phone no.**
European Economic Community	Environmentally benign air cycle, heat pumps and refrigeration systems	Main objectives for FKW are compressor and expander behaviour and optimisation	12/92 - 12/95	Dipl. Ing. S.Engelking Instute fur Kaltetechik und Angewante Warmetechnik. University of Hannover Welfengarten 1A D-3000 Hannover 1 p. 49 511 271 3879
Entre per Le Nuove Technologie, L'Energia E L'Ambient (ENEA), EU, Merloni Termo Sanitari (MTS), Italian Gas Utility (ITALGAS)	Air conditioning absorption heat pump	Test the technical and economical value of a single stage absorption heat pump utilising improved and advanced components such as plate heat exchangers, rectifier column, solution pump.	11/91 - 12/95	Paolo Giacmetti ENEA Cre-casaccio via Angullarese 301 00060 S. Maria di Galeria ROME p. 39 5 3048 3089
University and Scientific Research Ministry	Theoretical and experimental study of open cycle. [Padova University; Centre of Vicenza]	Use of absorbent materials for chemical dehumidification in an open cycle for air cooling.	1/94 - 1/98	Renato Lazzarin University of Padova p. 39 444 328090
Gas Research Institute (GRI)	Residential/Commercial Heat Pumps	Develop advanced gas heat pumps based on chemisorption technology	1987 - 1988	Gary Nowakowski Gas Research Institute 8600 W. Bryn Mawr Ave. Chicago, IL 60631 USA p. 001 312 399 8249 f. 001 312 399 8170
U.S. DOE	Thermally Activated Heat Pumps	Develop and commercialise advanced cycle concepts in absorption and engine-driven heat pumps for residential and small commercial buildings.	1982 - ongoing	Ronald Fiskum U.S. Dept. of Energy Forrestal Bldg. (5H-048); EE-422 1000 Independence Ave., SW Washington, DC 20585 USA p. 001 202 586 9130 f. 001 202 586 1628

14.5.3 Research on refrigerant environmental and safety issues

Since chlorofluorcarbon refrigerants have been widely used for over 50 years, most safety and handling concerns have long-since been resolved. Many of the proposed alternatives have yet to undergo extensive testing for safety concerns (toxicity, flammability, corrosiveness, etc.).

Investigating the safety of various alternatives is the Program for Alternative Fluorocarbon Toxicity Testing (PAFT), a co-operative research effort sponsored by chlorofluorocarbon producers. PAFT is designed to expedite the development of toxicology data for possible substitute fluorocarbons to replace CFCs. The programs integrate past and present toxicological information to perform a careful risk assessment. The six main types of studies conducted by PAFT include acute toxicity primarily by inhalation, genotoxicty, subchronic toxicity by inhalation, developmental toxicity/teratology, combined chronic toxicity and carcinogicity by inhalation, and environmental toxicity. PAFT has initiated more than 200 individual toxicology studies at a cost of $3-5 million per compound. PAFT program sectors are: PAFT I, which began in 1987, covers HCFC-123 (complete) and HFC-134a (complete); PAFT II, initiated in 1988, addresses R-141b (complete); PAFT III, begun in late 1989, is studying HCFC-124 and HFC-125; PAFT IV, established in May 1990, is examining HCFC-225ca (complete) and HCFC-225 (complete) for solvent cleaning; PAFT V, established in early 1992, is examining HFC-32. More than a dozen testing laboratories in Europe, Japan, and the United States are performing tests, the results of which are published in peer-reviewed journals and presented at scientific conferences. More information on the PAFT program can be obtained by contacting Dr. George Rusch, Toxicological Committee Chairman, PAFT, c/o AlliedSignal, Inc., P.O. Box 1139, Morristown, NJ 07962-1139, USA; tel: 201/455-3672, fax: 201/455-5405.

15 Historical global CFC consumption (1986-1993) and near future demand and supply

15.1 Introduction

This section provides data on the historical global CFC consumption after 1986 and estimates on the near future CFC needs for maintaining CFC refrigeration and air conditioning equipment operable after the CFC phaseout in 1995 in the developed world. These data have been largely assembled from chemical manufacturer sources.
The data assembled provide a picture of the total CFC use since 1986 by the using industries. An attempt has been made to allocate CFC use between developed countries (separated with respect to CEITs, countries with economies in transition), Article 5(1) countries and countries which are no Parties to the Montreal Protocol. The data assembled here will provide insight into the remaining challenge to reduce and phase out global CFC use after 1993/1994, as well as insight into the remaining CFC needs for refrigeration and air conditioning.

15.2 Methodology and data sources

It is difficult to obtain current accurate figures for CFC use or production. The most reliable global source is believed to be data accumulated by an independent audit of production and sales from the twelve companies that comprise the AFEAS group. This effort builds on the original data gathering exercise started by the fluorochemicals producers under the U.S. Chemical and Manufacturers Association (CMA) Fluorochemical Program Panel (FPP). The CMA and AFEAS group also report an estimation of their share of total world CFC production; this permits estimating global CFC production and sales (use).

Japan Flon Gas Association (JFGA) provides market data and production figures for the combined Japanese Fluorocarbon producers. Similar data are gathered by CEFIC, the Western-European fluorocarbon industry trade group.

UNEP data are incomplete but significant information exists in document UNEP/OzL. Pro 5/5, published in 1993 (Bangkok 17-19 November 1993), as well as in the same type of document (UNEP/ OzL. Pro 6/5), published in 1994. Data in these reports permit verification of the U.S., Japan and Western European information as well as a few benchmarks for other important producers and users of CFCs.

U.S. data have not been made public by the U.S. government or trade groups beyond what appears in the above mentioned UNEP document. Data from a large global fluorocarbon supplier of CFCs that has a reasonably comprehensive data base have been used to quantify the U.S. as well as other markets. A report by the U.S. Congressional Research Service (April 1993) and several trade magazine articles were examined to verify or fill in data gaps. It would appear that the aforementioned data sources seem to be the source of all other published numbers; hence it is easy to fall into a circular verification trap.

UNEP/OzL.Pro/ExCom/8/25 (21 September 1992) presents estimates of the total ODS usage for Article 5(1) countries only. Data presented in this section are consistent with those in the 1992 UNEP study.

15.3 Data analysis

Table 15.1 (see also Fig. 15.1) presents a summary of the best available information for global consumption or sales in the years 1986 through 1993 (from CMA/ AFEAS sources as well as from separate chemical manufacturer data). Some important observations from table 15.1 are:

- The total CFC use in the developed countries (excluding CEITs) has declined by 65% over the period 1986-1993, from 862 kt in 1986 to 302 kt in 1993.
- In the same time frame, it appears that the total CFC consumption in CEITs and Article 5(1) countries has remained in the 250 to 270 kt/year range.
- By 1994 it is expected that the CFC use in the developed countries (excluding CEITs) world will be comparable to or below the use in the rest of the world (being the CEITs and the Article 5(1) countries).

Figure 15.1 Global consumption of CFCs, 1986-1992

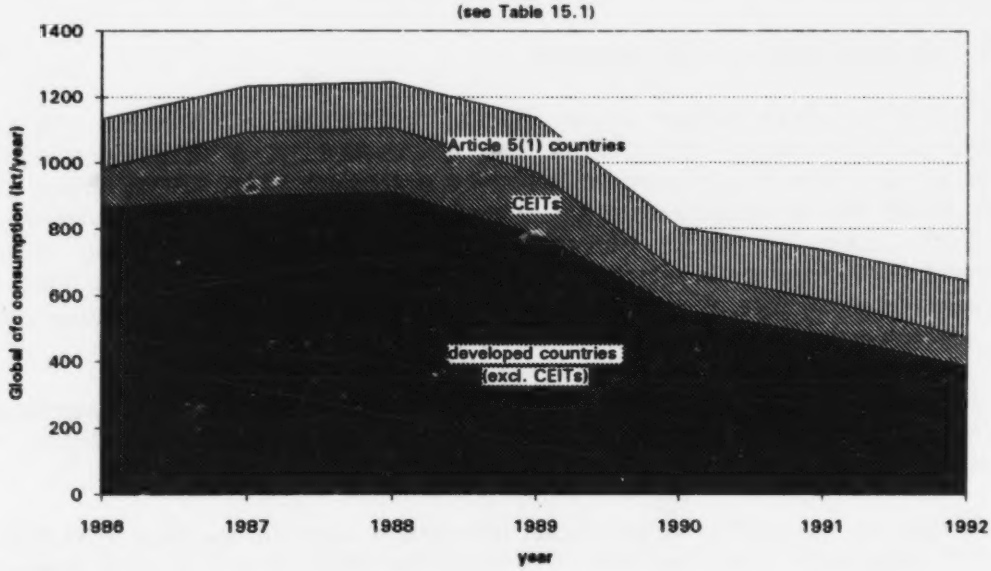


Table 15.2 summarises the actual global sales of each specific CFC chemical by the twelve AFEAS companies. The AFEAS data were also adjusted by the estimated percent of total global sales to permit an approximation of the total and individual CFCs sales.
Table 15.3 breaks out the refrigeration segment data from Table 15.2 (by extrapolation from CMA/AFEAS data); it also presents an estimate from a global producer as an additional check on the accuracy or reasonableness of the data. Table 15.4 is an attempt to determine how much CFC refrigerant could be inventoried globally (not charged into

equipment but available for future use somewhere in the distribution chain); as well as to estimate future fluorocarbon type refrigerant demand for vapour compression equipment.

At best, any figures related to inventory build-up are estimates but it seems that some inventory build up can be inferred from the sales peaks in the 1987 to 1989 time frame (30 to 70 kt). Based on various government actions and trade comments it is likely that additional CFC inventory could be accumulated in 1994 and 1995, as production and consumption allowances may exceed near term demand. This latter CFC inventory may be 80 to 170 kt, or 35 to 65% of the annual global demand. As the footnotes in Table 15.4 explain, there are significant changes in market dynamics that are decreasing the size of the CFC- and CFC-alternatives markets. The combination of smaller refrigerant charges in new equipment, no venting regulations, high excise taxes (U.S. market primarily), higher CFC prices and a concerted effort to eliminate CFC waste has reduced the total global refrigerant market by about 25% from historical volumes and has also reversed the 2.9%/year. global growth rate that existed in the decade preceding the 1987 Montreal Protocol. The best estimate of future fluorocarbon demand (see line (4) in Table 15.4), will be met by a combination of:

- smaller charges in new equipment
- improvement in containment
- recycle and recovery of CFCs from old equipment,
- recycle of CFCs from retrofit of equipment with HFCs and or HCFCs.
- replacement of CFCs in the new, equipment market (OEM), by the use of CFC alternatives, hydrocarbons and not-in kinds;
- continued use of CFCs in the developing countries.

Global experience in curtailing CFC use has occurred under a wide range of government and private sector activities. The following observations apply:

- In the U.S., the combination of no venting or other use prohibitions, a rapidly accelerating excise tax, several national solvent and refrigerant recycle programs and a rapidly growing retrofit market have not only reduced overall CFC use by about 65% but cut refrigerant use by 50% from 1986 to 1993.
- The European Union has relied heavily on volume reduction schedules to meet their year end 1994 total phaseout date. However, despite progress in other sectors, in the 1986 to 1993 time frame total refrigerant use has remained constant or increased slightly (by 19% in 1993 compared to the 1986 reference year).
- Japan has used a strong industry/government partnership and annual reduction schedules to accomplish its total CFC reduction that includes about a 25% cut in refrigerant use between 1986 and 1992 (being the latest year for which data are officially available).

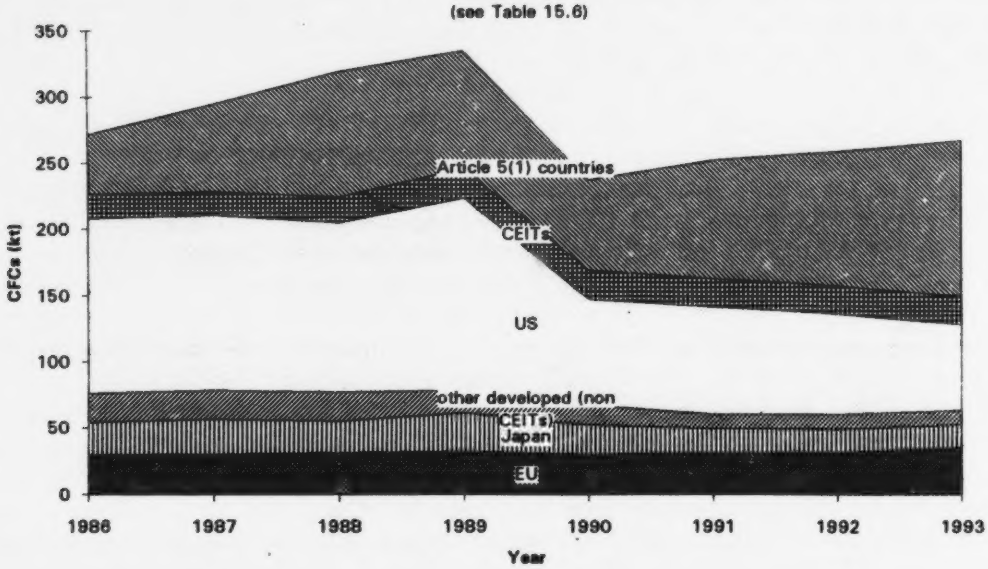
Table 15.5 presents data which makes it possible to understand the changes in the global refrigerant market. Several changes need to be emphasised:

- The global original equipment markets (OEM) have converted more than 40% of new equipment production lines from the use of CFCs, as of 1993. The developed countries may be able to realise a conversion percentage higher than 90% by the end of the year 1994.
- The global CFC refrigerant service market has decreased by about 40 kt in a 3-5 year period which is almost 20% (see Table 15.5, line 2). In Table 15.6 (lines 1, 2, and 3) it can be observed that most of this decline has taken place in the U.S. market.
- The decrease in refrigerant consumption for servicing purposes has been reasonably balanced across the four markets listed in Table 15.5. While many believe that automotive air conditioning (50-60 kt/year) is the largest user of CFC-12, the data suggest that the use of refrigerants in stationary small, medium and large

refrigeration systems is larger, and equals about 90 kt/year (however, this 90 kt figure has considerable uncertainty since it has been obtained by subtracting the sum of all other uses, and could well have a 20 kt uncertainty). Most of this stationary equipment is installed in the developed countries, but the share of the developing countries is not insignificant.

Table 15.6 (see also Fig. 15.2) presents a summary of the refrigerant use in the developed countries (excluding CEITs) and extrapolates the consumption by the other countries, i.e. CEITs and Article 5(1) countries.
From these data it can be observed that, while a 38% reduction in global refrigerant use has occurred, there was still a demand of 129 kt in the developed countries (excluding CEITs).

Figure 15.2 Global consumption of CFC refrigerants, 1986-1993



The two tables (Tables 15.5 and 15.6) provide a good summary of the developed country and the global refrigerant markets. As of 1993, the global CFC refrigerant use was about 200 kt, where 60-65% was used in the developed countries, however, the other 35-40% in other countries.
Table 15.5 presents the global use of CFC refrigerants, while Table 15.6 presents a "rough" estimate of the CFC refrigerant use by the CEITs and the Article 5(1) countries. Data in Table 15.6 (line 9) suggest that the use of CFC refrigerants in the CEITs and Article 5(1) countries may have doubled since 1986; and the use in these countries could be comparable in 1994 to the use in the developed countries (excluding CEITs).

Table 15.7 presents an estimate of the available CFC production from production facilities in Article 5(1) countries as well as data concerning the 15% allowance for "basic domestic needs", which will be potentially available from developed world plants. The potential supply may be 338 kt per year, assuming that the 15% allowances will all be produced.
On the other hand, the near future CFC refrigerant needs in 1994/1995 are around 200 kt globally, which estimates suggest substantial excess supply. However, if the demand in

the Article 5(1) countries for CFCs for aerosol products, blowing agents, etc., will remain significant, the estimated excess supply could be much more modest.

15.4 Future CFC needs

The appendix summarises miscellaneous data, assembled from various sources, which makes it possible to obtain a better insight in the current and future CFC (or CFC alternatives) requirements for the servicing of existing refrigeration and air conditioning equipment. This is a rough extrapolation but it should give an idea of the range of CFCs, HCFCs, or HFCs needed to service the stock of CFC based (not HCFC-22) equipment that is dependent upon fluorocarbons for their remaining useful and economic life.

The figures in the table below should give an impression of the future quantities of CFC refrigerants (not for new equipment) needed for the servicing of CFC based technologies (which figures do not deal with the HCFC-22 based equipment). Most of this equipment base can be found in the developed countries.

Table: Fluorocarbon refrigerants for servicing (kt), based on two retirement scenarios (5 and 25% annually), for the period 1994-2000

		1994	1995	1996	1997	1998	1999	2000
1)	5%/yr. replacement or retrofit for existing equipment (maximum case)	170	162	153	146	138	132	125
2)	25%/yr. replacement or retrofit for existing equipment (minimum case)	155	116	87	65	49	37	35

The data presented in the table above do not deal with the CEIT/ Article 5(1) countries' CFC refrigerant use for servicing which will be very likely in the 65-75 kt/yr range after 1994 (with a growth rather than a reduction in consumption in the above given timeframe).

15.5 CFC recycle potential

The CFC recycle volumes are going to be dependent upon the equipment inventory or "bank" of refrigerants in these systems. The "bank" can be used as internal recycle when equipment is serviced, and can be made available for other use at the moment when equipment is retrofitted or replaced. In other cases, contamination can lead to disposal.

European experience suggests that 50% of CFC refrigerant sales are for servicing installed or existing equipment (the U.S. figure is 75% which may be influenced by the large fleet of automotive air conditioners). In Europe, an average equipment life of ten years is generally assumed. By using the refrigerant data from Table 15.6 for the U.S., Japan, and the E.U. (lines 1, 2 and 3) and adding estimated quantities of 180 kt and 175 kt for 1985 and 1984, respectively, this would provide a total 10 year refrigerant use for these 3 regions of 1624 kt.

Assuming that 50% was for servicing purposes and 50% was for use in new equipment, the bank would be 50% of the 1624 kt, or 812 kt. On an annual basis, it is possible that 10%, being 81 kt, is potentially available for recovery. Using the U.S. experience that 25% of refrigerant sales is for the use in new equipment, this would suggest that about 400 kt (rather than 812 kt) would be inventoried in existing equipment. In this case, the potential amount available for recovery would be about 40 kt.

Another approach is to examine actual recovery experience. The E.U. data for 1993 indicate that about 1000 tonnes (equal to 3% of the 1991-1992 E.U. sales) was recovered in central facilities. Applying this 3% figure to the 1993 sales in the U.S., Japan and the E.U., it would lead a potential recovery quantity of about 9000 tonnes per year (3% of 302 kt). This recovery rate sounds very low compared to the annual recovery potential of 40-80 kt, but it must be recognised that internal recycle or storage at the users' sites is likely quite significant.

The U.S. experience is not much different from the E.U. experience, in terms of refrigerant tendered to recovery stations for purification and resale.

Based on this very limited experience for recovery plus the fact that the U.S. and Japan markets for CFC refrigerants have declined significantly, it can be assumed that internal recycling is possibly an order of magnitude larger than the amount returned to the open market for general use.

Table 15.1 Total CFCs consumed [a] or sold in different countries or regions, and global use (kt), compare Table 15.2

		1986	1987	1988	1989	1990	1991	1992	1993
1)	U.S.A. - Gov. data + Industry Est.	327	350	344	323	206	182	153	105
2)	Japan - Flon Gas data	133	156	159	161	111	96	61	46
3)	European Union CEFIC data	310	325	307	232	184	163	137	118
4)	Other developed UNEP data [c]	92	---	---	68	58	38	(35)[b]	(33)[b]
5)	Developed total (non CEITs)	862	---	---	784	559	479	(386)[b]	302
6)	CIS - UNEP data	120	---	---	110	110	---	---	---
7)	China - UNEP	19	---	---	26	35.5	43	---	---
8)	Article 5(1) countries as reported to UNEP	53	---	---	48	46	34	14	---
9)	Non Parties UNEP data	10	---	---	---	2	7	3	---
10)	Global sales [d] AFEAS producers	976	1063	1074	962	659	605	526	---
11)	AFEAS + estimate non reported prod.	1133	1233	1245	1137	802	736	643	---
12)	Unidentified to make total balance (lines 11-5-6-7-8-9)	69	---	---	169	49	173	240	---
13)	Use by Art.5(1) and CEITs, lines 11-5	271	---	---	353	243	257	257	---
14)	Use by Art.5(1),est.	151	---	---	243	133	---	170	---

a - All data has been tabulated as consumed or sold; not as produced since production is frequently different than sales due to inventory changes.

b - U.S./Japan/E.U. reduced 1993 use to 36% of 1986 base; assumed other developed countries did the same - 1993 value estimated at 33 kt. Estimated 1992 use for other developed countries: 35 kt.

c - UNEP data is taken from UNEP/0zL. Pro 5/5; Bangkok, November 1993.

d - The AFEAS companies report production and sales (by industry): they also estimate the amount of non AFEAS company production - see Table 15.2 for details.

Table 15.2 AFEAS reported global production for sale for all industries (kt)

		1986	1987	1988	1989	1990	1991	1992
	AFEAS COMPANIES [a]							
1)	CFC - 11	350	382	376	302	233	213	186
2)	CFC - 12	398	425	421	380	231	225	216
3)	CFC - 113	197	226	247	251	175	148	108
4)	CFC - 114	19	17	16.5	15	8.5	6.5	5
5)	CFC - 115	12	13	13.5	14	11.5	12.5	11
6)	Total	976	1063	1074	962	659	605	526
	AFEAS GLOBAL ESTIMATE [b]							
	11/12 Factors	0.85	0.85	0.85	0.81	0.74	0.75	0.75
	113/114/115 Factors	0.95	.95	.95	.93	.92	.91	.91
7)	CFC - 11	412	449	442	356	274	251	219
8)	CFC - 12	469	500	495	469	312	300	288
9)	CFC - 113	218	251	275	279	194	164	119
10)	CFC - 114	21	19	18	17	9	7.5	5
11)	CFC - 115	13	14	15	16	13	13.5	12
12)	Total	1133	1233	1245	1137	802	736	643

a - AFEAS companies report actual production and sales by product type (CFC 11-12, etc.) and by industry segment to an Auditor that assembles and publishes the results.

b - AFEAS experts on atmospheric CFC measurements examine all available data and make estimates on the reporting fraction of global productions included in the AFEAS report. Dividing by these factors provides a reasonable estimate of total world productions and sales.

Table 15.3 ***Estimates for global refrigeration use (kt) (CFCs only, HCFC-22 excluded)***

		1986	1987	1988	1989	1990	1991	1992	1993
	AFEAS COMPANIES ONLY [a]								
1)	CFC - 11	26	27.5	31	27	20	20	18	--
2)	CFC - 12	199	210	237	245	162	175	177	--
3)	CFC - 115	11.8	12.8	13.5	14.2	11.4	12.3	10.7	--
4)	CFC - 114/113	3.3	3.4	5.1	5.0	4.5	3.6	4.7	--
5)	Total	240.1	253.7	286.6	291.2	197.9	210.9	210.4	--
	GLOBAL AFEAS ESTIMATE [b]								
unreport factor-refrigerants		.95	.95	.95	.93	.92	.91	.91	--
6)	CFC - 11	27	29	33	29	22	22	19	--
7)	CFC - 12	209	230	249	263	176	192	195	--
8)	CFC - 115	13	14	14	15	12	13	11	--
9)	CFC - 113/114	4	4	5	5	5	4	5	--
10)	CFC Total	253	277	301	312	215	231	230	--
	GLOBAL INDUSTRY ESTIMATE [c]								
11)	All CFCs refrigeration	---	262	266	288	206	212	207	200
12)	AFEAS/industry est.	---	0.97	1.08	1.01	0.94	1.00	1.02	--
13)	World/industry est.	---	1.06	1.13	1.08	1.04	1.09	1.11	--

a - AFEAS producers' figures are actual data as reported to an Auditor.

b - Global AFEAS figures use an industry estimate and apply 1/3 of the AFEAS estimated factor unreported production. 1/3 was used knowing that a large portion of unreported production and sal in the C.I.S. and is primarily for aerosols and blowing agents; not refrigeration.

c - Industry estimate represents sum of estimates by all sales regions.

Table 15.4 *Global refrigeration (CFCs market only) 1986 - 1992, actual figures and future estimates, 1993-2000 (kt)*

		1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
1)	Global[a]	253	277[c]	301[c]	312[c]	215	231	230[d]	---	---	---	---	---	---	---	---
2)	Industry Est.[b]	---	265	270	295	210	220	215	225	200						
3)	Prod. for Inv. "guess"[g & c]		30 - 70 kt							50 - 100 kt						
4)	Best estimate of total fluorocarbon refrigerant "demand" or use[d + e + f +g + h]	250	250	240	230	210	230	230	230	230	210	190	190	195	200	210

a - Global AFEAS (Line 1) are sales figures factored to cover rest of world; see line 10, Table 15.3.

b - Industry global estimate based on global producers' sales estimates.

c - Table 15.3, data in line 10 suggests that world inventories may have increased in 1987, 1988 and 1989 by 30 to 70 thousand metric tonnes. This nventory will be worked off or used after 1995 and will reduce total CFC refrigerant sales (either new CFCs or HFC and HCFC alternatives).

d - Small charge sizes, mandated elimination of leaks or mandated refrigerant recovery have reduced refrigerant volume by about 50% in the largest market; the U.S.

e - AFEAS refrigerant CFC-12 sales data from 1977 (156 kt) through 1986 (198 kt) showed a growth of 42 kt in 10 years or a 2.9%/year compounded growth. At a 2.9%/year growth rate, 1992 CFC-12 data would have been 235 kt, or 58 kt higher than actual. This suggests that the market decreased by about 25%.

f - CFC-12 represented 78% of all CFC refrigerants in 1986. Increasing the 58 kt CFC-12 refrigerant reduction figure in (e) to 75 kt provides an approximation of the global total CFC refrigerant market reduction.

g - It is likely that another 50-100 kt of CFC refrigerants may be added in 1994 - 1995 to the 30-70 kt already in inventory. Therefore, future fluorocarbon refrigerant actual new production will (**consisting of both CFCs and HCFC / HFC alternatives**) be 80-170 kt below the use for a few years until the supplies and demands are balanced.

Table 15.5 Trends in refrigeration CFC use globally (kt), based on industry estimates

		1987	1988	1991	1992	1993
NEW (OEM) EQUIPMENT						
	Automotive AC, CFC-12	23	24	22	19	13
	Stationary CFC 11/12/502[d]	43	45	30	30	23
1)	Subtotal	66	69	52	49	36
AFTER (SERVICE) MARKET[c]						
	Automotive	75	71	50	50	57
	Stationary CFC 11	19	21	14	14	13
	Stationary CFC-12	100	103	83	91	90
	Stationary R-502[d]	10	10	8	9	7
2)	Subtotal[c]	204	205	155	164	167
3)	Total (OEM plus servicing)	270	274	207	213	203
AFEAS DATA FOR TOTAL GLOBAL REFRIGERANTS						
4)	All markets, all CFCs [a]	277	301	231	230	---
5)	Industry estimated data service as % of total CFC sales	76%	75%	75%	77%	82%
6)	"Best" service estimate [b]	209	225	173	177	---

a - AFEAS data include estimated quantity from non AFEAS companies, Table 15.3, Line 10.

b - Used industry estimated data and increased numbers to approximate AFEAS global figures, and combined "percentage" service figures in row 5.

c- By 1993, some CFCs were being displaced by HCFC-123, HFC-134a, and various HCFC/HFC blends; therefore the total service refrigerant use has been greater than 167 kt in 1993.

d- Only the CFC-115 content of R-502 is included in this figure.

Table 15.6 Trends in CFC refrigerant use for different parts of the world (kt)

	1986	1987	1988	1989	1990	1991	1992	1993
1) U.S.[a]	132	132	128	145	80	81	76	65
2) Japan[a]	24.3	26.1	23.7	28.5	21.7	18.3	17.7	17
3) E. U.[a]	29.9	30.2	31	32.6	30.2	31.2	31.5	35.6
4) Sub. Total[b] U.S/Japan/E.U.	186	188	183	206	132	131	125	118
5) Tot. CFCs[c] U.S./Japan/E.U.	770	831	810	716	501	441	351	269
6) % of total[d] CFCs used in refrigeration	24	23	23	29	26	30	36	44
7) Est. of other[e] developed (non CEIT) country refrigerant use	22	---	---	17	15	11	11	11
8) Est. of total[f] developed (non CEIT) country refrigerant use	208	---	---	223	147	142	136	130
9) "Rough" estimate of refrigerant use for Art.5(1)/CEIT countries[g]	45	---	---	89	68	89	101	117
10) Rough estimate for refrigerant use in Art.5(1)	---	---	---	64/70	43/49	65/71	77/83	93/99
11) Total CFC refrigerant use	**253**	**---**	**---**	**312**	**215**	**231**	**237**	**247**

a - Refrigerant data from Japan, U.S. and E.U. based on government, UNEP and trade group reports; with very good agreement. Estimated. U.S. 1986 figure based on 1987 & 1988 figures. Estimated 1993 figure for Japan.

b - Sum of lines (1), (2) & (3); Japan, U.S., and E.U. CFC refrigerants only.

c - Used line (1), (2) & (3) total CFCs from Table 15.1.

d - Line (1), (2) & (3) divided by line (5).

e - Line (4) Table 15.1 x line (6) fraction of other developed countries total CFC use (25-30%).

f - Sum of line (1), (2), (3) and (7).

g- Line (10) from Table 15.3 is the estimated total world refrigerant use. Subtraction of line (8) above (estimated total developed (non CEIT refrigerant use) provides a "rough" estimate of CFC refrigerant use in the Article 5(1) plus CEIT countries.

Table 15.7 Potential CFC production after 1995 (kt)

	1986 PROD. [a]	EST. CAPACITY [1]	15% ALLOWANCE [2,b]
E. U.	429	N.A.	64
Japan	132	N.A	20
U.S.	354	N.A.	53
China		30 → 70	
Latin America	?	48	
Taiwan	?	Shutdown?	
India	?	25	
Eastern-Europe	?	10	
C.I.S.	120 [d]	?	18 [d]
S. Africa		10	
Korea		20 [c]	
Sub-total for column (1) & (2)		183 +	155
Potential supply summary of columns (1) and (2)			338[e,b]

a - Base figure used to calculate 15% post 1995 allowance for sales for basic domestic needs of Article 5(1) countries. The 15% allowances are not ODP adjusted.

b - Some of the 15% allowances may not be available past year end 1995, therefore these figures could be 20-50 kt lower.

c - Korea is considered Article 5(1) country.

d - Question is whether the C.I.S. will produce 15% of the 1986 base. Production has substantially decreased over the period 1991-1994 from the original 120 kt capacity.

e- If the total former USSR production (in the C.I.S.) will be available beyond year end 1995, it could raise the potential total by about 60-100 kt above the 338 kt figure.

(1) & (2) Are the estimated capacity and 15% allowance values for Article 5(1) and the developed countries.

Appendix

Data On Future Service Needs For Refrigeration And Air Conditioning Equipment

1. MACS Mobile Air Conditioning Service Data Book (Mobile Air Conditioning Society, March 1994)
   - 35-38 kt of CFC-12 needed or 80-87% of potential 1994-1995 U. S. production.
   - Service profiles on older cars

1-3 year old vehicles	5.2% of all service
4-5 year old vehicles	21% of all service
6-7 year old vehicles	27.6% of all service
1-9 year old vehicles	19.4% of all service

   - 50% of vehicles serviced had 50-100 thousand miles.

2. Industrial Chiller Service Needs for CFC-11 - Industry Estimate

	'94	'95	'96	'97	'98	'99	'00	'01	'02
kt @ 5%/yr. leak rate	2.4	2.1	1.8	1.6	1.4	1.3	1.3	1.2	1.1
kt @ 10%/yr. leak rate	4.7	4.2	3.6	3.2	2.9	2.7	2.5	2.3	2.2

3. Industrial Chiller Service Needs for CFC-12 and R-500 - Industry Estimate

	'94	'95	'96	'97	'98	'99	'00	'01	'02
kt @ 5%/yr. leak rate	0.8	0.8	0.7	0.7	.6	.6	.6	.5	.5
kt @ 10/yr. leak rate	1.7	1.6	1.4	1.4	1.3	1.2	1.1	1.0	1.0

4. Global Automotive Fleet Service Needs for CFC-12 UNEP TOC Refrigeration Section 10, May 1994 Draft

	'94	'95	'96	'97	'98	'99	'00	'01	'04
kt	45.8	42.5	39.3	36.1	32.2	28.8	25.6	---	14.1
cumulative (kt)	45.8	88.0	128	164	196	225	250	---	---

5. Domestic refrigerator/freezers
   - 1988 U. S. D.O.E. Report figures on global production
     -54.7 million units globally
       8.5 million U. S. A.
       13.8 million Western Europe
       4.8 million Japan
     -130 million units operating in U.S.A.
   - 1993 AHAM data and personnel communication (L. Swatkowski, AHAM, Chicago)
     -58 million units total global production
       9.5 million in U. S. A.
     -150 million units operating in U. S. A.
     - CFC-12 refrigerant charge per unit

U. S. A.	170 g/unit
Europe	100 g/unit
Japan	mid-range of U. S. A./Europe
global average	155 g/unit

     - Appliance useful life

U. S. A.	16-18 years
globally	20 years

- **Estimate of global production**
  U. S. A./Japan/Western Europe markets saturated and have comparable ratios of units in service to 1998 production and used past growth data averaged or 2%/yr. from 1988 to 1994.

	Millions of units - 1988		Millions of units - 1994
- Annual production		in service	in service
U. S. A.	8.5	130	
Europe	13.8	210	
Japan	4.8	75	
Total		415	465

- Estimated appliances in service figures for rest of world:
  - Using 1988 global figure (54.7 million units/yr. production) and a compound growth rate of 8%/yr. for new units yields the following:
    27 million new units made in 1988
    42 million new units made in 1994

  Using new growth at 8%/yr. and a 20 yr. life (5%/yr. retirement) for old units suggests that the non-developed world in service figures could be 460 million units by 2000. Assuming 4500 to 5000 million people in the world outside of U. S. A./Japan/Western Europe, this would be one unit for every 10 people, which sounds too high. At 20 persons per refrigerator, the number of units outside of U.S.A./Japan/Europe would be approximately 250 million units.

- Best estimate for total world refrigerator/freezer in service figure in the 1995 to 2000 time frame is:

U. S. A./Japan/Western Europe	450 million units
Other countries	250-450 million units

- Service on U. S. A. refrigerators is about 2%; estimate is that service may be 3 times as much in the rest of world, which would be 6%. Using an average of 155 g/unit, the CFC-12 charge yields estimated service values as follows:

	kt/year
U. S. A./Japan/Western Europe	1.4
Article 5(1)/ CEIT	2.3 - 4.6
Global use	3.7 - 6.0

- Service projection through 2005

	'95	'96	'97	'98	'99	'00	'01	'02	'03
U. S. A./Japan/ Western Europe	1.4	1.4	1.3	1.2	1.2	1.1	1.1	1.0	1.0
Other countries			2.3-4.6→ → → → → → →						

Assumes that U. S. A./Japan and Western Europe have converted all new refrigerators by '96; the same for the CEIT and Article 5(1) countries by 2000. Furthermore that old appliances are retired at a 5%/year rate (20 year life time for world inventory); it assumes that the rest of the world growth is offset by retirements until 2000.

6. Low temperature equipment using R-502 (50% CFC-115)

- Global estimates of CFC-115 are reasonably accurate due to the small number of producers. The data for production is as follows:

(kt)

	'86	'87	'88	'89	'90	'91	'92
CFC-115	12.5-13	13-14	14-15	14-16	11.5-13	12-13	11-12

  - Most global production will be shutdown or converted to alternatives by year-end 1994. Retrofit to HFC/HCFC blends will likely be the only option coupled with reuse of R-502 from retrofitted equipment.

7. Summary of what is known about global refrigerant markets and future CFC service needs:

- In 1987-1988, before Montreal Protocol went into effect, the global CFC refrigeration and air conditioning service needs may have been 270-274 kt/yr (data from Table 15.5, line 3)
- In 1991-1992, after Montreal Protocol went into effect, the global CFC service needs may have been 207-213 kt/yr.(data from Table 15.5, line 3).
- Service needs in 1994 may be approximated as follows:

- Mobile A/C (CFC-12) [(a)]	40-45 kt
- Miscellaneous CFC-12 equipment [(b)]	88-96 kt
- Industrial chillers (CFC-11) [(c)]	5-13 kt
- Industrial chillers (CFC-12) [(c)]	2-5 kt
- Household refrigerants (CFC-12)[(d)]	4-6 kt
- R-502 low temperature refrigerants [(d)]	8-10 kt
- Total global CFC type refrigerants[(e)]	155-167 kt

- CFC type refrigerant service needs beyond 1994.
  - Future use will depend upon effectiveness of leak reduction programs, enforcement of no venting regulations in the nations that have such laws, extent of CFC retrofit with HFCs and HCFCs, and new equipment replacement of older CFC using equipment.
  - Most refrigeration and air conditioning equipment has a useful life of 10 to 40 years; with the average likely to be 20 years (at least in the developed world). Therefore, normal retirements would be about 5% of the equipment stock per year. Because of the CFC phaseout; retirements, retrofits, and replacements, realistically must be accelerated to 20-25%/year. Offsetting this will be new CFC equipment entering service in the Article 5(1) nations where the 10 year grace period allows.

(a) Using data from UNEP, Section 10, May 10 draft estimate; modified based on industry estimate.

(b) Calculated by difference to balance total global CFC type refrigerant line.

(c) Used industrial chiller estimates, item 2 of this Appendix, but assumed a 10-30%/yr. loss rate for the global population of existing chillers.

(d) Estimated from item 6 in this Appendix

(e) Estimated from year 1991-1993 data, Table 15.5, line 2. (This is an estimate of new production of CFCs, HCFCs, HFCs that may be required.) It must be remembered that these figures assume that inventoried new CFCs plus recycled and recovered CFCs are being used.

16 Historical global HCFC consumption and future demand

16.1 Introduction

This section is a follow-up to Section 15. Section 15 focused on CFCs and this section deals with estimates and scenarios for the use of transitional substances, or HCFCs.

16.2 Methodology and data sources

There are few published sources of HCFC production. There are no UNEP data since the materials do not come under control until 1996. The most reliable and complete data source is the AFEAS publication, "Production, Sales, And Atmospheric Release Of Fluorocarbons Through 1992". This document covers the CFCs and HCFC-22. AFEAS has also reported production data of HCFC-142b over the period 1981-1992 (showing a production which has increased from 2 kt in the early 1980s to about 30 kt of HCFC-142b in 1992 (Grant Thornton report, February 1994)).
Starting with 1993, the AFEAS report will bring in other CFC fluorocarbon alternatives when three or more producers report a combined production of ten thousand metric tonnes per compound. The 1993 AFEAS report is not expected to be available until sometime in 1995, hence, the only published data cover HCFC-22.

The UNEP Ad Hoc Work Group on Process Emissions and Inadvertent Production (1994 Progress Report of the UNEP Technology Panel) made point in time estimates for several CFC fluorocarbon alternatives which are used here to cross check the AFEAS information as well as projections by one global fluorocarbon producer.

16.3 Summary of data

Table 16.1 is a summary of the AFEAS HCFC-22 data and a single global producer's estimate for HCFC-22. These data have been tabulated as refrigerants and propellants/blowing agents. The AFEAS data are assumed to cover more than 95% of the global HCFC-22 production through 1992. The producer's data appears to represent about 80% of the total global amount; this can be observed from a visual comparison of lines 3 and 6, Table 16.1, between 1987 and 1992.

Table 16.2 (see also Fig. 16.1) is a factoring of the AFEAS and producer's data to approximate total global volumes; the AFEAS figures were increased 5% and the producer's figures were increased 20%. These "factored" figures suggest that global HCFC-22 refrigerant use has been in the 200 kt range for the last five years. As stated in footnote (d), Table 16.2, the HCFC-22 refrigerant demand in the world's largest segment, the U.S., has or will decline by about 25% from traditional levels due to smaller charges in new equipment and no venting regulations. It also is expected that this decline will lead to a flat HCFC-22 type refrigerant demand for the rest of the 1990 decade. HFC blends will likely displace some HCFC-22 but this cannot be forecast in this section.

Table 16.3 is an estimate of the other HCFC markets for blowing agents, propellants, cleaning agents, and miscellaneous refrigerants.

It contains the single year estimates from the UNEP Working Group document on Process Emissions and Inadvertent Production (line 1). Table 16.3 also contains the data for HCFC-22 refrigerants from Table 16.2, line 4 (line 3i). Also presented in the table is a single producer's estimate for HCFC and HCFC/HFC refrigerant blends used primarily to retrofit CFC-11, CFC-12, R-500, and R-502 equipment (line 3ii); the main exception is HCFC-123 which is also used in new industrial chillers.

Table 16.3 also presents a combination of HCFC blowing agents for plastic foam insulation and HCFCs (primarily HCFC-22) used as propellants where non-conductivity and non-flammability are a key technical requirement (line 4). The propellant volume is estimated at 5-15 kt per year and propellants are assumed to have converted from HCFCs by 1996. Therefore, all figures given for the years after 1995 are only for foam blowing agents. Some of the future blowing agent volume will convert to hydrocarbons (mainly cyclopentane and pentane mixtures) and it could convert to HFCs if suitable products become available.

Table 16.3 also presents data on solvents, i.e. less than 5% of the former CFC-113 market where CFC-113 could not be effectively displaced with other technologies (line 5). The HCFCs used here could be replaced by PFCs or HFCs if they become available.

Estimates for the total market for all HCFC type applications through the year 2000 are also given. It is expected that the maximum HCFC use will occur in the mid-1990s at a level of 340 to 360 kt/year; it will then start to decrease as suitable HCFC replacements will have been commercialised then.

Figure 16.1 Global consumption of HCFC-22, 1986-1992

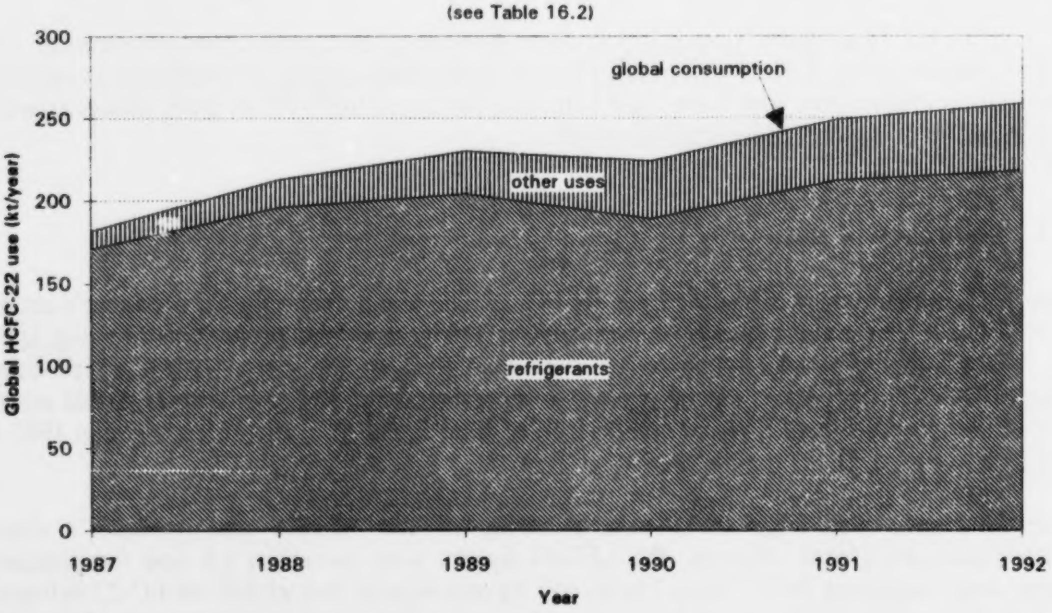


Table 16.1 *Estimated HCFC-22 global demand, all non feedstock uses (kt)*

	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992
I. AFEAS Report(a)													
1) Refrigeration	121	125	118	137	145	145	156	163	187	194	180	202	207
2) Propellants/ blowing agents	6	6	6	7	8	9	9	10	16	25	33	35	39
3) Total	127	131	124	144	153	154	165	173	203	219	213	237	246
II. Producer estimate(b)													
4) Refrigeration								163	173	172	162	172	180
5) Propellants + blowing agents								3	5	10	21	27	31
6) Total								166	178	182	183	199	211
7) Producer estimate % of AFEAS total								.95	.88	.83	.86	.84	.86

(a) AFEAS reported data is assumed to account for about 95% of total global HCFC-22 production reported for non-feedstock uses. Historically, 25% of annual sales went to new equipment manufacture and 75% went to service of existing equipment. The HCFC-22 figures also include the material used in R-502.

(b) The single global producer's estimate is typically only 85% of the AFEAS volume; therefore, these figures are approximately 80% of total global production for non-feedstock uses.

Table 16.2 *Estimated HCFC-22 total world demand for dispersive or non-feedstock applications (kt)*

	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
AFEAS Data(a)														
1) Refrigerants	171	196	204	189	212	218								
2) Blowing agents/ propellants	11	17	26	35	37	41								
3) Total	182	213	230	224	249	259								
Industry estimate b)														
4) Refrigerants(d)	---	---	206	194	206	216	220	205(c)	205	203	202	202	201	200

(it includes HCFC-22 and HFC alternatives for HCFC-22, values for HCFC-22 after 1993 will be 0-20 kt smaller)

(a) AFEAS data as reported, multiplied by 1.05 to approximate total global production. This accounts for material produced primarily in the C.I.S. states and China.

(b) The single global producer figures from Table 16.1, line 4 have been multiplied by 1.2 to approximate total global HCFC-22 for refrigerants.

(c) The U.S. market for HCFC-22 refrigerant is about 45% of the total global market; historically 25% OEM; 75% service. It is assumed that the U.S. market will shrink like the CFC-12 market (about 25%) due to the no venting laws and smaller refrigerant charges. The balance of the world market may also contract towards U.S. experience but with a few year's time lag.

(d) The balance of the 1990's could remain fairly steady at about 200 kt/yr. for HCFC-22 or HFC alternate refrigerants before the above mentioned 25% drop in market size would be assimilated and the market starts growing again. At a 4%/yr. growth it would take about 6 years to offset the 25% market loss. **The HCFC-22 market will be even less than indicated in line 4 as HFCs start to displace HCFC-22 in the OEM market by the mid 1990s. Pure HCFC-22 demand will be 0-20 kt smaller than figures given, over the period 1993-2000.**

Table 16.3 *Estimated global demand for all HCFCs excluding feedstock applications (kt)*

(HFCs are very likely to be substituted for some HCFCs so the figures for actual HCFC use will be lower.)

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	
1) Est.. by consultant(a)												
- HCFC-123						18						
- HCFC-141b/142b						136						
2) AFEAS data extrapolated(a)												
- All F/Cs as blowing agents						130					115	
- HCFC -123 refrigerant											10	
- Other HCFC refrigerant											10	
3) Industry estimate												
i - HCFC-22 refrigerants(b)	194	206	216	220	205	205	203	202	202	201	200	
ii - "Other" HCFC refrigerants(c)	1	1	1	5	6/8	10/15	10/20	15/25	15/25	16/27	15/27	
4) All HCFC Blowing Agents(d) and Propellants		22	38	58	86	117	125	130	130	120	105	100
5) HCFC Cleaning Agents(e)	---	---	---	5	6/12	8/13	8/14	10/15	10/15	10/15	10/15	
6)Total HCFCs - All uses(f)	217	245	275	316	335	355	360	365	355	340	335	

(a) Referencing the UNEP W.G. on Process Emissions and Inadvertent Production provides the following inputs:
- McCarthy 1993 est.; HCFC-123, HCFC-141b/142b, HCFC-22 for 1995 would be 18.2 kt, 136.4 kt, and 200 kt, respectively.
- AFEAS data extrapolated suggests that HCFC-22, HCFC-141b/142b, and HFC-152a use lumped together for foam blowing agents may be 130 kt in 1995. Inroads by hydrocarbons or other blowing agents will likely reduce volume to 100 kt in 2000 (other industry experts suggest a 115 kt value may be more realistic for 2000).

(b) HCFC-22 global refrigerant use is from Table 16.2, line 4. This includes HFC SUBSTITUTION AT AN UNSPECIFIED RATE, probably between 0 and 20 kt.

(c) A single global producer's estimate for "other" HCFCs is tabulated as a range in recognition that there are many factors affecting these refrigerants which are primarily used as CFC-12, R-502, and R-500 substitutes as well as HCFC-123 in large industrial chillers. Many of these blends contain HCFC-22 which has been removed and included in row 3i. The HFC content for row 3ii is 10-15%.

(d) The single global producer's estimate for blowing agents and propellants is comprised of all HCFCs and possible HFCs to approximate the total fluorocarbon market, exclusive of CFCs. The propellants represent 5-15 kt of the volume up through 1995 when it is assumed that HFCs will be used in place of HCFC-22.

(e) HCFC cleaning agents are being used to meet unique cleaning and drying requirements formerly met with CFC-113. This 10-15 kt global market could convert to PFCs or HFCs if suitable materials become available.

(f) Line 6 is the "best estimate" of global HCFC use in all markets. Figures beyond 1993 have an uncertainty of ±20%.

Annex I
Alternative Refrigeration Technologies

In this appendix a summary is given on alternative technologies, their main features, expected energy efficiencies, possible commercialisation etc. Data in this summary have been prepared by a small group of selected TOC members and this information has already been used for the larger part (after review) for a Special Supplement to the UNEP Ozonaction Newsletter (Ozonaction, Special Supplement no. 2, ISSN 1020-1602, UNEP IE, Paris, September 1994). AFEAS also intends to publish on "in-kind" and "not-in-kind" alternative technologies, however, a peer reviewed publication was not available at the moment this TOC Refrigeration Report had to be finalised (by the end of November 1994).

In this appendix a short review is given first of the specific properties of vapour compression and the refrigerants used. Thereafter the different "in-kind" (such as hydrocarbons and ammonia) and "not-in-kind" technologies are shortly described.

A1 Vapour compression and the refrigerants applied

Vapour compression is the most commonly used technology for refrigeration and air conditioning. It uses a compressor, two heat exchangers, an expansion device (e.g. capillary tube, orifice plate, thermoexpansion valve), and a working fluid (refrigerant). The vapour compression cycle still has potential for a substantial increase in efficiency by the use of different drives, mixtures of refrigerants, enhanced heat exchangers, and more efficient air movers. The process of optimising design for efficiency is still ongoing. Although refrigeration started with a large number of refrigerants in the 19th and 20th centuries (ethers, CO_2, hydrocarbons, methyl chloride, NH_3, SO_2), all had disadvantages and there were limitations with the equipment available at that time. Ammonia and hydrocarbons have seen continued, albeit limited use in certain types of equipment in the 20th century.

A1.1 Fluorocarbon vapour compression

CFCs and HCFCs have been used as refrigerants since the 1930s. Both of these classes of compounds are scheduled for phase-out under the Montreal Protocol. HFCs have been developed as replacements for CFCs and HCFCs and significant effort has gone into redesigning equipment to use these refrigerants. HFC refrigerants are available for immediate use for chillers, unitary equipment, automobile air conditioning, and transport and commercial refrigeration. All applications currently suffer some efficiency deficiency under certain design conditions and development efforts are directed toward correcting these problems and attaining efficiency improvements.

End-use equipment costs will be slightly higher than costs for CFC and HCFC equipment with even greater increases when a high pressure HFC is used. Costs of converting compressor and system manufacturing facilities are lower than for most other alternative technologies. Obstacles to development have included identification of compatible lubricants, engineering plastics, and motor winding insulation's; optimisation of heat transfer surfaces; improving refrigerant containment to minimise emissions to the atmosphere; and developing thermodynamic properties for new HFCs. These obstacles have now been overcome for HFCs for most refrigeration and air-conditioning applications, and better energy efficiencies are achieved in most newly designed equipment. Energy efficiency is an important aspect in selecting alternatives, therefore all technologies need to be seriously considered as to how far they can compete in terms of performance.

A1.2 Non-fluorocarbon vapour compression

Hydrocarbons:
Hydrocarbons have been used successfully for a long time as refrigerants in industrial applications. European, mainly German, companies have recently successfully manufactured household refrigerators using isobutane as the working fluid and some preliminary studies have been conducted in Europe and the U.S. on using propane in unitary air-conditioning systems. While still lagging behind HFCs in development, household refrigerators using hydrocarbons are commercially available and unitary air conditioners and other applications could be available in the medium term, subject to many safety and training issues being resolved. Cost factors for equipment using hydrocarbon refrigerants vary by application.

Although substantial investments are needed to convert the manufacturing facilities to use isobutane (up to 30% more than an HFC conversion), and although the high purity isobutane refrigerant is comparable in price to HFCs, hydrocarbon refrigerators are still comparable in costs to HFC refrigerators. European, mainly German companies have now commercialised refrigerators using isobutane as the working fluid (where a 30% market share is expected world-wide by the TOC Refrigeration in 3 to 5 years) and some preliminary studies have been conducted on using propane in unitary air-conditioning systems. Costs for unitary air conditioners using hydrocarbons could be up to 30% higher than costs for HCFC-22 based air conditioners. Hydrocarbons can be introduced in the very short to medium term (dependent on the application) and deserve serious consideration where they safely be applied and provide enhanced efficiency.

Ammonia:
Ammonia is a common chemical manufactured on a large scale, primarily for non-refrigeration applications, and is inexpensive. Ammonia has a large potential for expanded use in refrigeration at reasonably short notice (also due to changes in regulations, e.g. in Europe). A significant cost would be incurred in the application of ammonia in small systems if intermediate heat transferring means have to be applied (heat exchangers filled with a non-toxic, non-flammable fluid) and in obtaining necessary building permits. Technical obstacles delaying the expanded use of ammonia include development of hermetic compressors, new lubricants providing part solution and enhanced heat transfer surfaces for heat exchanger tubes. Ammonia is also restricted by regulations and building codes that deter potential users from using it.

In the US, 81% of refrigerated warehouses operate on ammonia systems; in Germany, about 60% of cold storage and food processing systems use ammonia.

Carbon-dioxide:
Vapour compression systems are also under development which would use carbon dioxide as the refrigerant. The high-side pressure of these systems exceed the critical point of carbon dioxide, so condensation does not occur in the high-side heat exchanger, but otherwise these systems are very similar to conventional vapour compression systems. Conceptually, CO_2 systems are under consideration for stationary air-conditioning

systems and also for automobile air conditioners. A prototype has been developed for an automobile air conditioner, but commercialisation is not likely before the end of this decade. Broad use in other applications is probably on a similar time scale. Equipment costs are likely to be comparable to slightly higher than for systems using HFCs or hydrocarbons. The further efficiency improvements and the very high operating pressures are the greatest obstacles to successful development and acceptance of this technology coupled with the availability of engineers and service technicians with skills unique to these products.

Water:
Water can be used as the refrigerant in vapour compression systems which operate above the freezing point of water (0 C) such as water chillers for space conditioning. These systems require high volumetric flow rates and operate at extremely low suction pressure and high pressure ratios. The energy efficiency is high, and the efficiency of the system can be further increased by pumping "ice" solutions to the conditioned space; this procedure has already been commercialised. The compressor costs are three to eight times those of a conventional compressor. Systems have been commercialised in large capacity industrial applications (with continuous operation) where energy efficiency is the dominant factor in the life cycle costs of the equipment (e.g. in mining applications with for long pipelines to the space to be cooled). The system can be open and can provide demineralised water on the condenser side. Demonstration projects have started which apply smaller units for building applications where the cost of the compressor is important in the life cycle costs. Further development of the system, in particular the issues of "size" and "cost" is needed before a larger scale commercialisation will take place.

A2 Sorption, gas-cycles and other cooling technologies

Evaporative cooling:
An evaporative cooler works to lower the dry bulb temperature of the air in the conditioned space, either directly or indirectly, by evaporating water from a spray or a porous media. The sensible heat of the air is used to evaporate water, reducing the air temperature, and providing a more comfortable air supply. Evaporative coolers are immediately available for use in residential and some commercial applications in dry climates. Systems can be designed to use evaporative cooling in conjunction with vapour compression air conditioning or desiccant dehumidification. Advanced combined systems for use in regions with moderate humidity could be available in the mid-term. Equipment costs for direct systems where the water is evaporated directly by the supply air are lower than costs for vapour compression air conditioners; additional costs are incurred for ducted systems because of evaporative coolers require larger ducts than vapour compression air conditioners. Costs for indirect or combined systems will be higher. Evaporative cooling is not accepted by many as providing acceptable comfort levels even in climates best suited for its use and is inappropriate for moderate and high humidity climates. Improvements in performance and public perception are needed to expand its use in existing markets and into more humid climates.
Evaporative cooling air conditioners have been manufactured for residential and industrial applications in the US, as well as in developing countries.

Absorption:
Absorption is a heat activated alternative to the vapour compression. It uses a pair of chemicals, the absorbent and the refrigerant, heat exchangers, an expansion device, an

absorber, and a gas burner or generator in direct fired equipment (steam or waste heat are also used). The chemicals used (e.g. ammonia/water, lithium bromide/water) are neither ozone depleting compounds nor greenhouse gases, although they are very corrosive causing significant materials issues.

Many different absorption refrigerators are being marketed, but these often suffer from low efficiencies unless costly extra components are included. Fossil fuel (natural gas) or solar energy heated absorption refrigerators fulfil a certain need in areas that have no access to electricity. Single- and double-effect water chillers for air conditioning are also commercially available. Triple-effect chillers are under development and in the long term could provide efficiency improvements. Several manufacturers produce absorption heat pumps, although very few are in use. High efficiency, GAX absorption heat pumps are being produced for field testing and could be commercially available around 1998. Equipment costs are higher than for vapour compression systems to provide the same service. Absorption systems must reject greater amounts of heat than compression chillers and heat pumps so larger, more expensive, heat exchanger surfaces needed. Financial incentives from gas suppliers may offset all or part of the higher equipment costs, which could make the absorption chiller or heat pump extra attractive.

Adsorption:

Adsorption refrigeration systems are similar to absorption except they are based on the adsorption of the refrigerant onto a solid instead of absorption of the refrigerant into a liquid. A heat source is used to desorb the refrigerant from the solid at high temperature and pressure. Adsorption has been proposed for residential sized heat pumps and for automobile air conditioners. Field testing of heat pumps could occur in 1997 to 1998 with possible commercialisation two or more years later. Testing of adsorption air conditioning for automotive use has so far been unsuccessful and adsorption is now being tested for application in trucks and buses; commercialisation is unlikely to occur in the short term. Large volumes are required for cycling adsorbent bends in operating systems which adversely influences the cost level. Commercialisation of automobile air conditioners is unlikely before the end of this decade. Significant size and cost reductions of adsorption systems are necessary and efficiency and long term performance must be demonstrated for this technology to be viable in consumer products.

Stirling-cycle:

The Stirling refrigeration cycle is derived from the principle that when constrained within a fixed volume, a gas rises in pressure when it is heated. Both external combustion engines and refrigeration systems have been designed and constructed using the Stirling cycle and either hydrogen or helium as the working fluid. The Stirling cycle has been applied successfully to cryogenic systems. So far one reference is available that reports efficiencies from prototype tests comparable to vapour compression for certain temperature differences (outside/inside temperatures). Generally, the prototype Stirling cycle systems are less efficient than vapour compression systems using either fluorocarbon or hydrocarbons at conditions for household refrigeration or space conditioning. One of the important issues still to be resolved is reliability of the system over a lifetime (e.g. 100,000 hours as required in household refrigeration). Significant investment is necessary to commercialise the Stirling cycle and it is unlikely that competitive reliable products could be available before 2000. Widespread use of Stirling cycle equipment for space conditioning or refrigeration is probably a long-term prospect. Reduced efficiencies resulting from auxiliary power requirements for pumps and fans and high unit costs are obstacles limiting commercialisation. Significant developments in methods to transfer heat from inside the refrigerator cabinet or conditioned space to the Stirling unit (e.g. heat pipes) are needed as are significant cost reductions.

Air-cycle:

The so-called Joule cycle is a compression/expansion gas cycle with gliding temperatures in the heat exchangers and any refrigerant can be used in the cycle. Air has reasonable properties and is applied because it yields the possibility to "open the cycle" using the air from the space to be cooled as the refrigerant. The cycle needs a direct connection of the compressor and expander and high isentropic efficiencies of both components to make it competitive with compression with evaporation and condensation. The simple air cycle configuration yields rather low efficiencies and technical measures need to be taken to improve the efficiency (heat exchangers, two stage cycle). Comparison of a COP of a practical vapour compression cycle with the COPs calculated for the 'best' possible air cycle show 0 to 30% lower efficiencies for the air cycle in the temperature range -30 to -10°C using an 80% isentropic efficiency. It should be emphasised that this comparison is only for calculated performance and air cycle machines have not yet reached the efficiencies quoted above. The air cycle can be "GWP competitive" for non-hermetic, emissive refrigeration and air-conditioning applications since no refrigerant leakage occurs in the air cycle (direct emission contribution zero). The air cycle is considered to be a relevant alternative after vapour compression, however, practical applications are limited. Some pilot applications are expected before the year 2000 for certain applications (transport trucks and railway refrigeration and air conditioning). Significant developments are still needed in efficiency and cost effective turbine/compressor constructions.

The European Union has funded a three year research project (Joule II) to develop air cycle heat pumps, air conditioning and refrigeration systems for specific applications.

Electric- and magnetic-refrigeration:

Thermoelectric refrigeration and magnetic cooling are entirely different technologies which share some of the same problems. Thermoelectric refrigeration is based on the Peltier effect which produces heat at one junction and cooling at another when an electric current is passed through a semiconductor. Magnetic cooling is based on the magnetocaloric effect of entropy changes which occur when very high magnetic fields are applied alternately to certain materials. These two technologies are similar in that both require significant breakthroughs in materials to be viable in consumer products and neither is a likely alternative to vapour compression except in the long term. Magnetic cooling is projected to have very high costs because it requires superconducting magnets and very rare metals (e.g. gadolinium). Breakthroughs in high temperature superconducting materials are needed for magnetic refrigeration.

Thermoelectric refrigeration has very low efficiency and couples with figures of merit 50 to 100% higher than the best developed under laboratory conditions are needed for thermoelectric refrigeration to be competitive with vapour compression. It therefore also requires a breakthrough in order to be viable in consumer products.

Liquid CO_2 and N_2:

Direct gas expansion of liquid nitrogen or carbon dioxide is sometimes used for transporting perishable products (e.g. frozen foods). The process involves spraying liquid carbon dioxide or liquid nitrogen into the loaded trailer or rail car, the very cold spray absorbs large amounts of heat as it expands and evaporates, chilling the product for shipment. The rail car or trailer does not carry a mechanical refrigeration system; saving the fuel cost for the extra weight this would entail and refrigerant losses and mechanical problems resulting from the highway or rail vibrations. This technology is already in use by some companies and is immediately available for use by others, but has limited applicability. This method is much less energy efficient (50 to 100 times) than vapour compression refrigeration. There is a trade-off in refrigeration energy use, transportation energy use for a vapour compression system, and maintenance costs that make direct gas expansion appropriate in some circumstances. This technology is not confronted by major technical obstacles requiring R&D, however its use should not be recommended due to the extreme emissions of CO_2 for the refrigeration effect provided.

Thermoacoustic cooling:

Thermoacoustic cooling uses a sound wave to generate a temperature gradient to provide useful cooling, reversing a phenomena observed by glass blowers centuries ago who found that an intense temperature gradient could generate a sound wave. Although several prototype refrigeration units have been built, this technology is at a very early stage and is very unlikely to be commercialised even in the mid-term.

Thermoacoustic refrigeration could use HFCs or hydrocarbons as the refrigerant or helium. Lubricant/refrigerant miscibility is not an issue using HFCs or hydrocarbons as the refrigerant; no lubricant is required because the only moving part exposed to refrigerant is a "loudspeaker" to generate the sound wave. It is far too early in the development of thermoacoustic cooling to speculate on production or consumer costs. Commercialisation is constrained by needs for further development of heat exchanger geometry's unique to this technology, the design of the resonant cavity to eliminate shock waves, acoustic power levels for domestic refrigeration, improved electroacoustic conversion efficiencies, and secondary heat transfer loop performance for refrigeration loads greater than 100 W.

Table A1 Advantages and disadvantages of 0 ODP refrigerants.

Advantages	Disadvantages
HFCs: immediately available, high efficiency, low to moderate GWPs, non-toxic, non-flammable, excellent thermodynamic properties (commercialised)	**HFCs:** most have moderate GWPs
HC: very low GWP, high efficiency, excellent thermodynamic properties (commercialised)	**HCs:** flammable; mixtures difficult to optimise
NH_3: zero GWP, excellent thermodynamic properties (commercialised)	**NH_3:** toxic, flammable in some conditions, material incompatibilities
CO_2: GWP of one, non-toxic, non-flammable, well known properties	**CO_2:** very high pressures, low efficiency; high equipment costs
H_2O: negligible GWP, widely0 available, non-toxic, non-flammable, high efficiency (commercialised)	**H_2O:** low suction pressure and high volumetric flow rate (large compressor), high compressor costs

Table A2 Advantages and disadvantages of alternative refrigeration and air conditioning technologies.

Technologies	Advantages in New Equipment	Disadvantages
Evaporative Cooling	negligible GWP, high efficiency in dry climates (low electricity demand) (commercialised)	limited to dry climates, high air flow rates, higher equipment costs and service requirements, possible inferior comfort control
Absorption	zero GWP, can use waste heat, cost effective in some utility rate structures, potential for efficiency improvements, reliable (few moving parts) (commercialised)	low efficiency, high initial costs, requires large machine room, LiBr toxic, ammonia toxic and flammable in some conditions, viability is improved if waste heat is available
Adsorption	zero GWP, possible high heating efficiency, can use waste heat	low cooling efficiency, very large, high cost, not available in the short term
Liquid CO_2 and N_2	minimum GWP (if N_2), low maintenance for appropriate applications (commercialised)	very limited in applications, extremely low efficiency
Stirling Cycle	zero GWP, theoretical high efficiency, can be used over a wide range of temperatures	low demonstrated efficiency, long term reliability not demonstrated, not available in short or mid-term
Air Cycle	zero GWP, non-toxic low maintenance (running) costs	low efficiency, not economically feasible in many applications
Thermoelectric	zero GWP, immediately available, high reliability	very low efficiency, significant materials development required, practical for very small applications
Thermoacoustic	zero GWP	low efficiency, long term development required in order to become a feasible alternative
Ambient Cooling (surface & ground water, ambient air)	zero GWP	extremely site and application specific, limited application
Magnetic Cooling	zero GWP	very high costs, low efficiency, superconducting materials required, extremely high magnetic fields require shielding, very long term alternative

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